

Investigations of Production Cross-Sections of $^{122,123,124,125,126,128}\text{I}$ Produced in Te target by Proton Irradiation

Pawan Kumar^a & Sneha Lata Goyal^{b*}

^aDepartment of Physics, Govt College, Ateli 123 021, Haryana, India

^bDepartment of Physics, Guru Jambheshwar University of Sci & Tech, Hisar 125 001, Haryana, India

Received: 11th February 2026; accepted: 5th May 2026

The excitation functions of proton-induced (p, n) reactions on stable tellurium isotopes ($^{122,123,124,125,126,128}\text{Te}$) were investigated to evaluate their potential for producing medically important iodine radionuclides. Theoretical calculations were performed using the nuclear reaction model codes TALYS-2.0 and EMPIRE-3.2.3 and compared with experimental cross-section data from the EXFOR and ENDF databases. Both codes, employing different level density and pre-equilibrium approaches, were systematically assessed for predictive accuracy. The TALYS-2.0 generally reproduced the measured data more reliably across most isotopes, while EMPIRE yielded superior agreement for specific cases such as ^{124}I and ^{126}I production. Discrepancies between theoretical and experimental results underline the sensitivity of model parameters and the need for additional cross-section measurements, particularly in poorly explored energy regions. These findings highlight the importance of accurate nuclear data in refining reaction models and optimizing cyclotron-based production routes for radioiodine used in diagnostic and therapeutic applications.

Keywords: PCROSS, Pre-equilibrium, Talys-2.0, Hauser-feshbach, Level density, PET

1 Introduction

Proton-induced nuclear reactions play a central role in both nuclear physics and radiochemistry. They not only help us understand the dynamics of nuclear interactions but also serve as the foundation for producing radioisotopes that have wide-ranging applications in medicine and industry¹⁻². One of the most important tools in the study of these reactions is the measurement of excitation functions, the variation of reaction cross-sections with proton energy. These measurements provide essential information such as reaction thresholds, the dominant production channels, and the relative influence of different mechanisms, including direct interactions, compound nucleus formation, and pre-equilibrium processes³⁻⁵. Beyond their value for advancing fundamental nuclear science, excitation function studies have practical significance. They guide the optimization of radioisotope production by improving yields, reducing unwanted by-products, and minimizing excess radiation exposure in clinical environments⁶⁻⁸.

Tellurium isotopes are of particular significance because (p, n) reactions on stable Te nuclei yield a range of iodine radioisotopes with established roles in

nuclear medicine^{9,10}. Among them, ^{123}I ($T_{1/2} = 13.2$ h, $\gamma = 159$ keV) is regarded as an optimal tracer for single-photon emission computed tomography (SPECT), widely applied in thyroid imaging and neurological diagnostics such as Parkinson's disease¹¹. ^{124}I ($T_{1/2} = 4.2$ d), a positron emitter, is well suited for positron emission tomography (PET), enabling long term tumour imaging and bio distribution studies of radio labeled biomolecules¹². ^{125}I ($T_{1/2} = 59.4$ d) is extensively used in brachytherapy, particularly for localized cancers of the thyroid and prostate, due to its emission of low-energy γ rays (27–35 keV) and Auger electrons that provide highly localized radiation doses. It also plays a central role in radio immune assays, facilitating ultrasensitive biomolecule detection¹³. By contrast, ^{128}I ($T_{1/2} = 24.99$ min) has a very short half-life, limiting its use to short-duration experimental studies in nuclear physics¹⁴. Collectively, these diverse applications highlight the clinical and scientific importance of studying Te(p, n) excitation functions.

Furthermore, the discrepancies observed between theoretical predictions and experimental measurements highlight the need for continued refinement of nuclear level density models, alongside the acquisition of new experimental data in underexplored energy

*Corresponding author: E-mail: goyalsneh@yahoo.com

regions. In situations where direct measurements are difficult—such as for isotopes with very short half-lives or where technical limitations restrict experimental access—reliance on robust theoretical modelling becomes essential⁴. This work presents a systematic investigation of excitation functions for proton-induced (p, n) reactions on stable isotopes of tellurium, employing the advanced nuclear reaction model codes EMPIRE-3.2.3 and TALYS-2.0. The calculated cross sections are rigorously benchmarked against experimental data compiled in the EXFOR database¹⁵ as well as evaluated nuclear data libraries¹⁶, thereby enabling a critical assessment of model reliability and predictive accuracy.

The production of radio iodine from tellurium targets has been investigated using experimental measurements, evaluated datasets, and theoretical modelling. However, previous studies vary significantly in terms of the isotopes examined, the energy ranges considered, and their research objectives. Early high-energy measurements of ¹²⁵Te(p, xn) reactions, particularly for generating ¹²⁴I, remain an important benchmark for proton-induced production routes up to 100 MeV¹⁷. The evaluation studies, including the widely cited work¹⁸, combined proton and deuteron data to recommend production routes, energy windows, and thick-target yields for ¹²⁴I, contributing substantially to practical production planning. Other groups measured proton-induced cross sections on natural tellurium and compared the results with TALYS and EMPIRE simulations, pointing out regions where model predictions deviate from experiments¹⁹. More recent applied studies have shifted toward the optimization of ¹²⁴I production, including thick-target yield measurements and improvements in irradiation strategies for clinical applications²⁰.

Despite these contributions, most previous investigations either limited their focus to one or two isotopes (typically ¹²⁴I) or explored only low and intermediate proton energies (< 30–40 MeV). In contrast, the present study delivers a consistent and systematic evaluation of production cross sections for six iodine isotopes (¹²²I, ¹²³I, ¹²⁴I, ¹²⁵I, ¹²⁶I, and ¹²⁸I) produced from tellurium using a 100 MeV proton beam.

2 Nuclear Model Codes

2.1 Empire-3.2.3

EMPIRE-3.2.3²¹ is a comprehensive nuclear reaction code system developed under the

International Atomic Energy Agency (IAEA) for advanced modelling and evaluation of nuclear processes. It can generate nuclear data over a wide energy range—from the keV scale to several hundred MeV for different projectiles, including neutrons, protons, heavy ions, and photons. The code is designed in a modular framework that brings together multiple theoretical approaches. These include optical model calculations, pre-equilibrium dynamics, and compound nucleus decay, all integrated within a single computational environment. This unified architecture enables consistent treatment of complex reaction mechanisms, such as proton-induced neutron emission (p, n) reactions), within one simulation platform. Because of its versatility, EMPIRE has become an essential tool in nuclear data evaluation, reactor design, and the optimization of production routes for medical isotopes. The global parameterizations²² have been used in the present study with two specific input configurations:

Empire1: Generalized Superfluid Model (GSM) level densities combined with the PCROSS-1.5 pre-equilibrium model.

Empire2: GSM level densities coupled with both Hybrid Monte Carlo Simulation (HMS-1) and PCROSS-1.5 pre-equilibrium models.

2.2 TALYS-2.0

TALYS-2.0²³ is a comprehensive nuclear reaction code capable of simulating a wide range of processes, including proton-induced (p, n) reactions, across energies from 1 keV up to 200 MeV and for targets covering much of the nuclear chart. The code integrates several advanced theoretical approaches, such as optical model potentials, the Hauser–Feshbach statistical theory, and exciton-based pre-equilibrium models. Together, these frameworks allow TALYS to generate accurate predictions of reaction cross-sections, energy spectra, and angular distributions. For (p, n) reactions in particular, TALYS provides a consistent description of direct interactions, pre-equilibrium dynamics, and compound nucleus mechanisms. This makes it especially valuable for estimating production cross-sections that are critical to nuclear medicine, reactor design, and astrophysical studies. Its extensive parameter libraries, combined with compatibility with experimental databases such as EXFOR¹⁷, further strengthen its role in nuclear data evaluation and model validation. As a result, TALYS has become a widely used tool for optimizing radioisotope production pathways and investigating nucleosynthesis processes,

serving as a robust platform for both applied and fundamental research. In the present study, TALYS calculations were carried out using the Constant temperature Fermi gas model for nuclear level densities, the exciton model for pre-equilibrium dynamics, numerical transition rates with energy-dependent matrix elements (Pair model = 1) and other parameters were taken as default.

2.3 χ^2 - Test: Goodness of Fit

The χ^2 test²⁴⁻²⁵ is one of the most widely used statistical methods for evaluating the consistency between theoretical predictions and experimental data. It measures the degree of deviation using the statistic

$$\chi^2 = \sum (O-E)^2/E \quad \dots (1)$$

where O represents the calculated (or observed) values and E corresponds to the experimental (or expected) data. The resulting χ^2 value is then compared with critical values from the χ^2 distribution to assess the statistical significance of the fit. Commonly known as the goodness-of-fit test, this method regards a fit as satisfactory if the computed χ^2 is smaller than the tabulated value at the chosen significance level and for the relevant degrees of freedom. The degrees of freedom, defined as $n = k - 1$, are determined by the number of data points (k) included in the comparison. To further refine the evaluation, the reduced chi-square (χ^2/n), which normalizes χ^2 by the degrees of freedom, is also employed. The probability value (p -value)²⁴ provides a measure of the probability that the discrepancies between calculated and experimental cross sections are attributable solely to statistical fluctuations, assuming the validity of the theoretical model. A comparatively high p -value (>0.1) suggests that the deviations lie within the limits of expected experimental uncertainties, thereby indicating satisfactory agreement between model and measurement. Conversely, a very low p -value (<0.05) implies that the observed differences are unlikely to

arise from random variation alone, pointing to a significant shortcoming of the model in reproducing the excitation functions.

3 Results and Discussion

Excitation functions for radionuclides produced through (p, n) reactions on stable tellurium isotopes have been investigated using the nuclear reaction model codes EMPIRE-3.2.3 and TALYS-2.0, employing a range of input parameters. The calculated excitation functions were systematically compared with available experimental cross-section data as well as with the evaluated results from the MENDL-2¹⁸ library. The experimental datasets were adopted directly from the EXFOR database without any renormalization. The model predictions exhibiting the closest agreement with experimental observations are presented graphically, while the corresponding decay data are summarized in Table 1²⁶. The statistical evaluation of the fits, expressed in terms of reduced chi-square values, is provided in Table 2. The cumulative number of levels $N(E)$ for each iodine isotope was determined using experimental level information from the ENSDF²⁷ database and compared with the cumulative curves generated by EMPIRE and TALYS. As expected, an excellent agreement is observed in the discrete-level region (Fig. 1), because both reaction codes use the RIPL-3 nuclear structure library, which is derived from ENSDF²⁷ evaluations. This agreement confirms that the discrete level schemes have been correctly incorporated into the models. Furthermore, the smooth continuation of the theoretical curves demonstrates that the selected level-density models in EMPIRE and TALYS are appropriate and reliable for the present study.

3.1 ¹²²Te (p,n)¹²²I

The calculated excitation function for the ¹²²Te(p,n)¹²²I reaction is presented in Fig. 2. The experimental data for this reaction remain scarce, largely owing to the short half-life of ¹²²I,

Table 1 — Decay data of radioisotopes²⁶

Reactions	E _{th} (MeV)	Spin, Parity	Reaction product	Half -life	Mode of decay (%)
		J π			
¹²² Te(p,n) ¹²² I	2.48	1+	¹²² I	3.63 min.	EC β^+ (100)
¹²³ Te(p,n) ¹²³ I	2.59	5/2+	¹²³ I	13.22hours	EC β^+ (100)
¹²⁴ Te(p,n) ¹²⁴ I	3.99	2-	¹²⁴ I	4.17 days	EC β^+ (100)
¹²⁵ Te(p,n) ¹²⁵ I	2.73	5/2+	¹²⁵ I	59.40 days	EC β^+ (100)
¹²⁶ Te(p,n) ¹²⁶ I	2.52	2-	¹²⁶ I	12.93 days	EC β^+ (52.7) β (47.3)
¹²⁸ Te(p,n) ¹²⁸ I	2.06	1+	¹²⁸ I	24.99 min	EC β^+ (6.9) β (93.1)

Table 2 — Reduced chi square Values						
Reaction	Experimental data	Theoretical data	χ_{red}^2	Prob. Value (p-value)	Energy Range (MeV)	Degree of Freedom
$^{122}\text{Te} (p,n) ^{122}\text{I}$	Hohn <i>et al</i>	TALYS	0.34	0.9	6.1-9.0	4
		E1,E2	0.63	0.6	6.1-9.0	4
$^{123}\text{Te} (p,n) ^{123}\text{I}$	Mahunka <i>et al</i>	TALYS	0.57	0.8	12.2-17.8	8
$^{124}\text{Te} (p,n) ^{124}\text{I}$	Scholtan <i>et al</i>	TALYS	1.18	0.3	12.8-20.5	9
		E1,E2	0.83	0.6	12.8-31.2	13
$^{125}\text{Te} (p,n) ^{125}\text{I}$	Hohn <i>et al</i>	TALYS	0.77	0.7	27.8-45.2	9
$^{126}\text{Te} (p,n) ^{126}\text{I}$	Scholtan <i>et al</i>	TALYS	0.62	0.9	17.6-99.9	19
		E2	0.69	0.8	40.5-99.9	11
$^{128}\text{Te} (p,n) ^{128}\text{I}$	Azzam <i>et al</i>	TALYS	1.86	0.1	6.1-9.81	6
		E1, E2	1.58	0.2	6.1-9.81	6

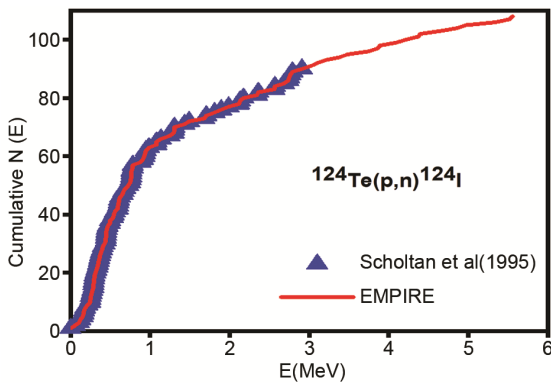


Fig. 1 — Comparison of the cumulative number of levels $N(E)$ as a function of excitation energy

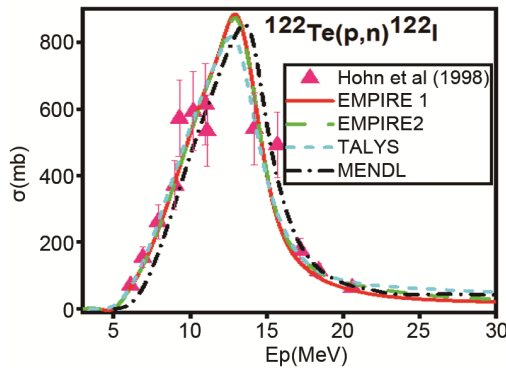


Fig. 2 — Excitation function of $^{122}\text{Te}(p,n)^{122}\text{I}$ with proton energy up to 30 MeV

underscoring the importance of theoretical modelling. The computation performed with the Fermi-gas level density option in TALYS-2.0 exhibit fair agreement with the available measured data²⁸, spanning from threshold energy across the entire investigated range within experimental uncertainties. Similarly, EMPIRE-3.2.3 calculations successfully reproduce both the overall trend of the measured excitation function and the evaluated nuclear data. Furthermore, results obtained with EMPIRE-1 and EMPIRE-2

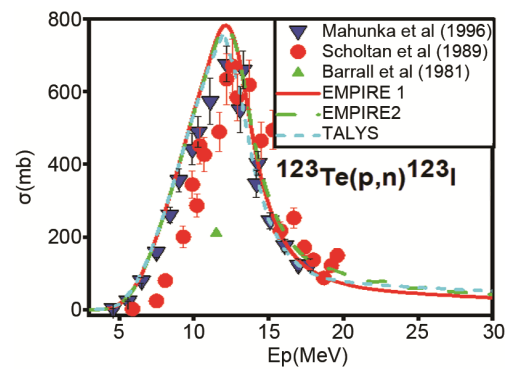


Fig. 3 — Excitation function of $^{123}\text{Te}(p,n)^{123}\text{I}$ with proton energy up to 30 MeV

employing the Generalized Superfluid Model (GSM) level densities demonstrate consistent agreement with the experimental data throughout the full energy interval. The computed results are consistent with previously reported literature data points²⁸ compared to evaluated data file MENDL below 16 MeV. So it is indicated that theoretical models predict well the measured data from energy range 6.1 to 20.6 MeV. The reduced chi square also confirms goodness of fit in low energy region. ^{122}I is a potential PET isotope due to its short half-life and positron emission. The accurate cross-section data are also essential for optimizing cyclotron-based production.

3.2 $^{123}\text{Te} (p,n) ^{123}\text{I}$

The $^{123}\text{Te}(p, n)^{123}\text{I}$ reaction channel opens at approximately 3 MeV, with experimental data available up to 19.6 MeV. The comparison between calculated excitation functions and literature data is shown in Fig. 3. The reported data point²⁹ is not in agreement with other measured literature data³⁰⁻³¹.

The results from both EMPIRE and TALYS are consistent with the earlier measurements³⁰ from threshold up to 18 MeV, except for minor deviations at the peak value, which remain within experimental

uncertainties. In particular, TALYS demonstrates reasonable agreement with existing data³⁰ in the 12.2–17.8 MeV range, as confirmed by the reduced chi-square analysis ($p = 0.8$). At lower energies (<12 MeV), the theoretical calculations tend to overestimate the prior studies³¹; however, above 12 MeV, the EMPIRE code, when employing the PCROSS pre-equilibrium and Hybrid Monte Carlo Simulation options, reproduces the experimental trend more closely, despite some uncertainties in the higher-energy region. These results indicate that compound nucleus evaporation dominates the reaction mechanism at lower energies, while at energies exceeding 15 MeV, competing channels such as (p,2n) and (p,3n) reduce the effective yield of ¹²³I. This reaction is of particular significance in nuclear medicine, as ¹²³I is a widely utilized radionuclide for single-photon emission computed tomography (SPECT), owing to its favourable half-life (13.2 h) and suitable gamma-ray emission characteristics.

Though ¹²³Te has a very little natural abundance and needs enrichment, the ¹²³Te(p, n)¹²³I reaction remains attractive since it yields ¹²³I with very high radio nuclidic purity and negligible unwanted by products. It can be carried out at comparatively low proton energies, which makes it appropriate for widely available small cyclotrons and helps limit competing reactions. Additionally, the enriched tellurium target can be recovered and easily reused, which helps bring down the overall production costs. Due to these reasons, this method is widely considered as a clean and highly efficient way to produce iodine-123.

3.3 ¹²⁴Te (p,n)¹²⁴I

The excitation function of the ¹²⁴Te(p, n)¹²⁴I reaction has been measured previously³²⁻³³, though their reported cross sections show discrepancies in the low-energy region (<16 MeV). A comparison of these experimental datasets and the evaluated MENDL library with theoretical results from EMPIRE-3.2.3 and TALYS-2.0 is presented in Fig. 4. The TALYS results are consistent with the data reported previously³² above 12 MeV, within experimental uncertainties, and this agreement is further supported by reduced chi-square analysis (Table 2). The calculations performed with EMPIRE, using the PCROSS+HMS pre-equilibrium option, also show good consistency with both MENDL evaluations and experimental measurements above 13 MeV. Furthermore, the results from TALYS, EMPIRE-1,

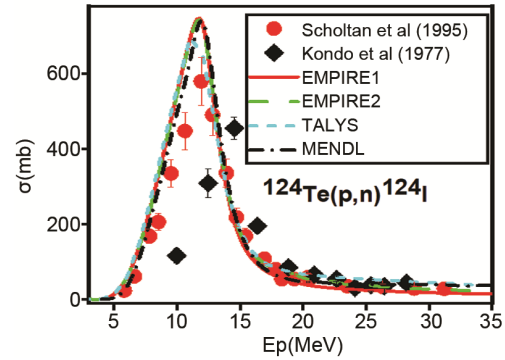


Fig. 4 — Excitation function of ¹²⁴Te(p,n)¹²⁴I with proton energy up to 35 MeV

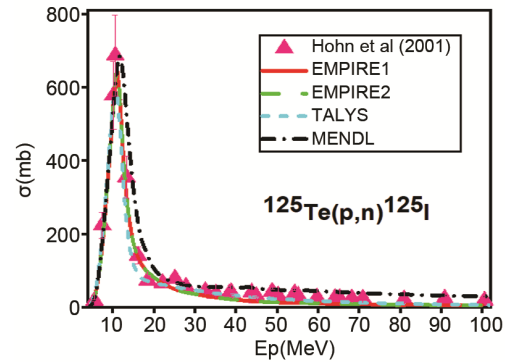


Fig. 5 — Excitation function of ¹²⁵Te(p,n)¹²⁵I with proton energy up to 100 MeV

and EMPIRE-2 reproduce the earlier findings³² in the lower-energy region, with deviations limited to the peak value. The pre-equilibrium component of the cross section is effectively modelled using the PCROSS and PCROSS + HMS options, as indicated by a reduced chi-square (p -value-0.6), confirming a statistically reliable fit. This reaction holds particular medical importance, as ¹²⁴I is a positron-emitting radionuclide with a half-life of 4.18 days, making it highly suitable for positron emission tomography (PET) imaging applications.

3.4 ¹²⁵Te (p,n)¹²⁵I

The comparison between theoretical predictions and available experimental data for the ¹²⁵Te(p, n)¹²⁵I reaction is presented in Fig. 5. The calculated cross sections show good agreement with the MENDL evaluation up to 10 MeV, while a slight underestimation is observed at higher energies. The results from TALYS exhibit reasonable consistency with the data reported earlier²⁸ across the full energy range, with a reduced chi-square analysis yielding a p -value of 0.7 in the 27.8–45.2 MeV energy interval. Similarly, excitation functions obtained using

EMPIRE-1 and EMPIRE-2 reproduce the experimental data²⁸ across the considered energy domain, with the exception of the peak region. These observations highlight the increasing role of pre-equilibrium (PEQ) emission processes in this reaction. However, PCROSS pre-compound model considers cluster emission, the (p, n) reaction here is mainly controlled by single-nucleon emission. When multiple or cluster emissions are comprised, the energy shared with other competing channels like (p,2n), (p, pn), (p, d), and (p, α). Due to this, less contribution remains for the (p, n) channel, leading to a decline in its computed cross section-especially at higher energies where these additional processes become more significant⁴. From an applied perspective, the $^{125}\text{Te}(p, n)^{125}\text{I}$ reaction is of considerable importance, as ^{125}I is a widely utilized radionuclide in oncology, diagnostic imaging, and biomedical research, owing to its favourable decay characteristics and production feasibility.

3.5 $^{126}\text{Te}(p, n)^{126}\text{I}$

Figure 6 illustrates the excitation function for the $^{126}\text{Te}(p, n)^{126}\text{I}$ reaction. The statistical analysis indicates a reduced chi-square p-value of 0.9 for TALYS in the 17.6–99.9 MeV energy interval and 0.8 for EMPIRE-2 in the 40.5–99.9 MeV energy range, suggesting that both codes reproduce the experimental trends with satisfactory accuracy. The TALYS results closely follow the data reported by earlier investigation³⁴ from threshold up to 17.6 MeV, with minor deviations near the peak, and overall show better consistency than the evaluated MENDL library. In contrast, EMPIRE agrees with both the experimental and MENDL data below 8 MeV but tends to overestimate cross sections in the 8–28 MeV range. The computations with EMPIRE-1 and EMPIRE-2 display a distinct hump around 14 MeV,

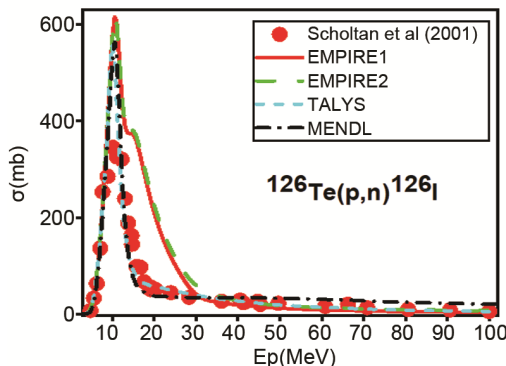


Fig. 6 — Excitation function of $^{126}\text{Te}(p,n)^{126}\text{I}$ with proton energy up to 30 MeV

likely reflecting the onset of additional open channels. The improved performance of EMPIRE with the PCROSS and Hybrid Monte Carlo Simulation options can be attributed to a more refined treatment of pre-equilibrium processes in heavier isotopes. The radionuclide ^{126}I , with a half-life of 13.11 days, is particularly valuable for short- to medium-term investigations in nuclear physics, radiochemistry, and radiobiology. It has been widely employed in studies of iodine uptake, metabolism, and thyroid function in experimental models, and also serves as an effective tracer in biochemical and environmental research, especially for elucidating iodine transport and behaviour in complex biological and chemical systems.

3.6 $^{128}\text{Te}(p, n)^{128}\text{I}$

Figure 7 compares the calculated excitation functions with experimental cross-section data for the $^{128}\text{Te}(p, n)^{128}\text{I}$ reaction. Notable discrepancies are observed in the low-energy region, where the measured cross sections differ significantly³⁵ from those reported in other studies^{1, 36}. The dataset extending up to 6 MeV³⁶ shows good consistency with theoretical predictions within the investigated energy range. In contrast, results from TALYS, EMPIRE-1, and EMPIRE-2 exhibit strong agreement with the earlier measurements¹ between threshold and 9 MeV. At proton energies above 9 MeV, both the experimental datasets and the MENDL evaluated data are well reproduced by TALYS and EMPIRE when employing the PCROSS+HMS option, with uncertainties effectively captured within the reported error bars. The results underscore the strong sensitivity of cross-section calculations to the choice of level-density formalism, while compound nucleus evaporation is consistently described under the selected modelling approaches. The radionuclide ^{128}I ,

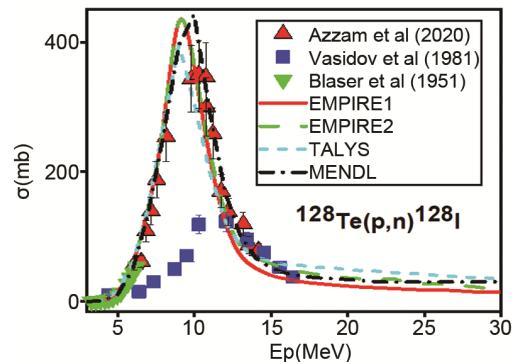


Fig. 7 — Excitation function of $^{128}\text{Te}(p,n)^{128}\text{I}$ with proton energy up to 100 MeV

with its short half-life of 24.99 minutes, is particularly well suited for time-sensitive experimental investigations in nuclear physics. Furthermore, the $^{128}\text{Te}(p, n)^{128}\text{I}$ reaction serves as an important probe of proton-induced reaction mechanisms, neutron emission pathways, and excitation function trends. These insights provide valuable input for nuclear data evaluations and contribute to refining isotope production models.

Below ~ 23 MeV, reaction dynamics are dominated by compound nucleus evaporation, producing the characteristic bell-shaped excitation functions. With increasing energy, the opening of competing channels such as (p, np) and (p,2n) leads to a reduction in the compound contribution. At higher energies (>23 MeV), pre-equilibrium emission becomes increasingly significant. In this regime, incomplete sharing of energy and momentum among nucleons results in particle emission with higher kinetic energies than those characteristic of the fully equilibrated compound system⁴. The ability of TALYS and EMPIRE to accurately reproduce these trends reflects the effectiveness of their compound and pre-equilibrium formalisms in modelling proton-induced reactions on tellurium isotopes.

4 Conclusion

The excitation functions for proton-induced reactions on tellurium isotopes ($^{122,123,124,125,126,128}\text{Te}$) were systematically evaluated with the aim of producing medically significant iodine radionuclides. The nuclear reaction model codes TALYS-2.0 and EMPIRE-3.2.3, implemented within the Hauser–Feshbach formalism, demonstrated strong predictive capability. Both TALYS and EMPIRE were able to reproduce the overall trend and magnitude of the experimental excitation functions within the experimental uncertainties. The reduced chi-square analysis confirms a good level of agreement between the theoretical predictions and the measured values, especially in the low- and intermediate-energy regions where the compound-nucleus evaporation mechanism is dominant. At higher projectile energies above 23 MeV, where pre-equilibrium effects become important, the inclusion of the PCROSS and Hybrid Monte Carlo Simulation (HMS) options in EMPIRE further improved the agreement with the observed cross-sections. The strong consistency between the output of TALYS and EMPIRE suggests that the chosen level-density models and optical model parameters are well suited for describing proton-

induced reactions on tellurium isotopes. The reliable theoretical predictions of (p,n) excitation functions are valuable for optimizing cyclotron-based production of medically important iodine radionuclides such as ^{122}I , ^{123}I , ^{124}I , and ^{125}I . Therefore, the present work provides a consistent and dependable set of nuclear data that supports both fundamental nuclear reaction research and practical applications in radiopharmaceutical production.

Acknowledgement

The authors gratefully acknowledge the financial support received from the Board of Research in Nuclear Sciences (BRNS), Department of Atomic Energy (DAE), BARC, Mumbai, under the Major Research Project (Sanction No. 2011/36/10-BRNS/0494).

References

- 1 Azzam A, Hamada M S, Said S A, Mohamed G Y & Al-abyad M, *Nucl Phys A*, 999 (2020)121790.
- 2 Parashari S, Mukherjee S, Naik B K, Naik H, Suryanarayan S V, Makwana R & Singh N L, *Nucl Phys A*, 987 (2019)128.
- 3 Kumar P & Goyal S L, *Indian J Pure Appl Phys*, 59 (2025) 330.
- 4 Kumar P, Goyal S L, Sarkar P K & Nandy M, *Indian J Phys*, 95 (2021) 325.
- 5 Matsushita K, Nishio T, Tanaka S, Tsuneda M, Sugiura A & Ieki K, *Nucl Phys A*, 946 (2016) 104.
- 6 Kumar P, Goyal S L & Nandy M, *Indian J Pure Appl Phys*, 59 (2021) 330.
- 7 Simeckova E, Majerle M, Stefanik M, Mrazek J, Novak J & Magna T, *Nucl Phys A*, 1016 (2021) 122310.
- 8 Kumar P, Goyal S L & Sarkar P K, *J Int Acad Phys Sci*, 21 (2017) 241.
- 9 Charity R J, *Phys Rev C*, 82 (2010) 014610.
- 10 Tarkanyi F, Hermanne A & Qaim S M, Guide to the Production of Medical Radionuclides, IAEA-TECDOC-1211, Vienna (2001).
- 11 Becker D V & Sawin C T, *Thyroid*, 6 (1996) 361.
- 12 Pentlow K S, Graham M C, Lambrecht R M, Daghighian F, Bacharach S L & Larson S M, *J Nucl Med*, 37 (1996) 1557.
- 13 Williamson J F, *Med Phys*, 29 (2002) 2501.
- 14 Firestone R B & Chu S Y F, Table of Isotopes, 8th ed., Wiley (1999).
- 15 Otuka N *et al*, *Nucl Data Sheets*, 120 (2014) 272.
- 16 Chadwick M B *et al.*, *Nucl Data Sheets*, 112 (2011) 2887.
- 17 Hohn A, Nortier F M, Scholten B, Van der Walt T N, Coenen H H & Qaim S M, *Appl Radiat Isot*, 55 (2001) 149.
- 18 Aslam M N, Sudár S, Hussain M, Malik A A, Shah H A & Qaim S M, *Appl Radiat Isot*, 68 (2010) 1760.
- 19 Kandil S A & Al-Abyad M, *Radiochem Acta*, 101 (2012) 67.
- 20 Bzowski P, Gorczewski D *et al*, *EJNMMI Phys*, 9 (2022) 42.
- 21 Herman M, Capote R, Carlson B V *et al*, *Nucl Data Sheets*, 108 (2007) 2655.
- 22 Koning A J & Delaroche J P, *Nucl Phys A*, 713 (2003) 231.
- 23 Koning A J, Hilaire S & Goriely S, *Eur Phys J A*, 59 (2023) 131.

- 24 Evans R D, *The Atomic Nucleus*, Tata McGraw-Hill, New Delhi (1955).
- 25 Kumar P & Goyal S L, *J Radioanal Nucl Chem*, 331 (2022) 3757.
- 26 Bevington P R & Robinson D K, *Data Reduction and Error Analysis for the Physical Sciences*, 3rd ed., McGraw-Hill (2003).
- 27 NUDAT-2.8 databases, Brookhaven National Laboratory, <http://www.nndc.bnl.gov/hbin/nudat>.
- 28 Hohn A, Scholten B, Coenen H H & Qaim S M, *Appl Radiat Isot*, 49 (1998) 93.
- 29 Barrall R C, Beaver J E, Hupf H B & Rubio F F, *Europ J Nucl Medicine Molecular Imaging*, 6 (1981) 411.
- 30 Mahunka I, Andó L, Mikecz P, Tcheltsov A N & Suvorov I A, *J Radioanal Nucl Chem*, 213 (1996) 135.
- 31 Scholten B, Qaim S M & Stöcklin G, *Appl Radiat Isot*, 40 (1989) 127.
- 32 Scholten B, Kovács Z, Tárkányi F & Qaim S M, *Appl Radiat Isot*, 46 (1995) 255.
- 33 Kondo K, Lambrecht R M & Wolf A P, *Appl Radiat Isot*, 28 (1977) 395.
- 34 Scholten B, Hassan K F, Saleh Z A, Coenen H H & Qaim S M, *Conf Nucl Data Sci Technol*, Nice (2007) 1359.
- 35 Vasidov A, Vakilova G & Muhammedov S, *Izv. Akad. Nauk Uzb. SSR, Ser Fiz-Mat Nauk*, 3 (1981) 93.
- 36 Blaser J P, Boehm F, Marmier P & Scherrer P, *Helv Phys Acta*, 24 (1951) 441.