



Estimation of Proton and Deuteron Induced Cross Sections for Radiomedical Technetium-99m Production

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Article's Information	Abstract
Received: 06.06.2025 Accepted: 12.04.2026 Published: 15.09.2026	The study calculates cross-sections for charged particles on molybdenum to produce the medical isotope technetium-99m and its parent isotope, molybdenum-99, both of which are crucial in nuclear medicine. Experimental cross sections for the following reactions: (d,3n), (d,n), (p,2n), (d,p), (d,x), and (p,x) were collected from the IAEA EXFOR library. We recalculated using MATLAB 2013 with an interval of 0.01, taking into account the error ratio for each researcher. The yield was calculated based on the calculated cross sections and stopping power, which were calculated using the SRIM 2013 and PSTAR codes. ¹⁰⁰ Mo(d,3n) ^{99m} Tc reaction, highest cross section 305 mb at E _d =24 MeV, yield=0.764 MBq/microAh at E _d =24.3 MeV. ⁹⁸ Mo(d,n) ^{99m} Tc reaction, highest cross section of 75 mb at E _d = 11.75 MeV, yield = 341 MBq/microAh at E _d = 12.2 MeV. ¹⁰⁰ Mo(p,2n) ^{99m} Tc reaction, highest cross section of 251.14 mb at E _p = 14.54 MeV, yield = 48.3 MBq/microAh at E _p = 19 MeV. ⁹⁸ Mo(d,p) ⁹⁹ Mo reaction, highest cross section of 244 mb at E _d = 8.7 MeV, yield = 108.6 MBq/microAh E _d = 12.7 MeV. ¹⁰⁰ Mo(d,x) ⁹⁹ Mo reaction, highest cross section of 41.14 mb at E _d = 35 MeV, yield = 0.025 MBq/microAh at E _d = 46.8 MeV. ¹⁰⁰ Mo(p,x) ⁹⁹ Mo reaction, highest cross section of 251.14 mb at E _p = 14.54 MeV, yield = 48.3 MBq/microAh at E _p = 19 MeV. Researchers should focus on deuteron-induced reactions and enriched isotopes for producing technetium-99, as these are a promising alternative to natural methods.
Keywords: Charged particle, Cross section, Technetium-99m, Yield.	

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1. Introduction

Ionizing radiation (α , β , γ , and neutrons) can harm living cells by breaking down molecules and altering biological systems, potentially causing DNA damage [1, 2]. In contemporary culture and scientific inquiry, radioisotopes are indispensable, especially in the field of medicine. Radiopharmaceuticals, which are chemical molecules that have been labeled with radioactivity, find widespread application in nuclear medicine. Radiation detectors are used to determine the distribution of radioactivity in radionuclides that are administered to patients as part of diagnostic procedures. The levels of hormones, antibodies, and drugs in the blood and tissues can be studied using radionuclide techniques. The last step in diagnostic procedures is radiation treatment, which treats tissues or organs in an effort to get them functioning

normally again [3, 4]. Technetium's radioactive isotopes, including ^{99m}Tc, are produced using cyclotrons. ^{99m}Tc is widely used in nuclear medicine due to its short half-life and broad gamma-ray spectrum. Radiopharmaceuticals derived from ^{99m}Tc account for 85% of the total, with their decay process taking 6 hours [5-7]. Due to its outstanding nuclear properties, it has recently gained popularity as a diagnostic tool in nuclear medicine. Gamma imaging techniques, like SPECT, benefit greatly from ^{99m}Tc's 140 keV gamma emission, which is the same as X-rays, which normally have a range of 20 to 150 keV as a medical tracer; its short half-life is an additional plus [6]. It is worth mentioning that ^{99m}Tc can be produced through the decay of its parent, ⁹⁹Mo, by beta emission with a half-life of 66 hours [7, 8]. It is feasible to conduct fission reactions using reactors

and the $^{235}\text{U}(\text{n},\text{f})^{99}\text{Mo}$ product [7, 9]. Producing ^{99}Mo has become significantly more challenging due to the fact that a limited number of research reactors have been rendered inoperable due to repairs, refurbishments, or deactivation [5]. Carrier-free radioisotopes are used in many industries; however, reactor failures resulted in the development of charged particle accelerators, making medium-energy particle accelerators a feasible choice for radioisotope synthesis [7]. Bombarding ^{100}Mo or ^{98}Mo with charged particles, such as protons and deuterons, can help address the strength of ^{99}Mo and $^{99\text{m}}\text{Tc}$. The natural abundance of these isotopes is relatively high: ^{98}Mo has an abundance of approximately 24.13%, while ^{100}Mo has an abundance of 9.63%. The production of $^{99\text{m}}\text{Tc}$ using charged particles has been studied by numerous researchers in previous years, including [6-9]. In this work, the production of $^{99\text{m}}\text{Tc}$ was investigated using two methods: direct production from these reactions, $^{100}\text{Mo}(\text{d},3\text{n})^{99\text{m}}\text{Tc}$, $^{98}\text{Mo}(\text{d},\text{n})^{99\text{m}}\text{Tc}$, and $^{100}\text{Mo}(\text{p},2\text{n})^{99\text{m}}\text{Tc}$. Indirect production by these reactions: $^{98}\text{Mo}(\text{d},\text{p})^{99}\text{Mo}$, $^{100}\text{Mo}(\text{d},\text{x})^{99}\text{Mo}$, and $^{100}\text{Mo}(\text{p},\text{x})^{99}\text{Mo}$ to produce ^{99}Mo , which subsequently decays into $^{99\text{m}}\text{Tc}$ as previously discussed, then the optimal reaction for the production of $^{99\text{m}}\text{Tc}$ and ^{99}Mo was determined.

2. Materials and Methods

This research is based on a systematic review and analysis of experimental data available in the EXFOR library for the production of $^{99\text{m}}\text{Tc}$ and ^{99}Mo .

2.1. Data Sourcing

The EXFOR library provided experimental cross-section data for ^{99}Mo and ^{100}Mo targets, containing details on the materials used by the original researchers:

- The use of MoO_3 enriched to 90% with ^{100}Mo for the (d,3n) reaction.
- The use of natural molybdenum ($^{\text{Nat}}\text{Mo}$) in metallic form for (p,2n) and (p,x) reactions.
- The use of high-purity, unenriched natural molybdenum ($^{\text{nat}}\text{Mo}$) for the (d,n) reaction.
- The use of ^{98}Mo enriched to 94% for the (d,p) reaction.
- The use of ^{100}Mo enriched to 90% for the (d,x) reaction.

2.2. Data Recalculation and Analysis

The cross-section data for each reaction were recalculated using MATLAB 2013, utilizing a statistical distribution of errors and a weighted average approach.

- Matlab-2013 was used to interpolate the closest data for each energy interval based on cross sections and their associated errors.
- Experimental cross-section data are collected from various authors and energy intervals, and rearranged based on the 0.01 MeV energy interval for each author's available energy range.
- The statistical distribution of cross-section errors has been standardized to align with the respective values for each author.

2.3. Stopping Power and Yield Calculation

The codes SRIM 2013 and PSTAR were used to calculate the stopping power and range of ions in matter for protons and deuterons in various materials, calculating the yield for each reaction.

3. Theory and Formula

3.1. Cross Section

The cross-section is a fundamental quantity in nuclear physics that represents the probability of a nuclear reaction. The experimental cross-section data are interpolated and averaged to derive a single, recommended value. To calculate the weighted average cross section, the following equations are used [10]:

$$\sigma_{w.a.} = \left(\sum_{i=1}^n \frac{\sigma_i}{(\Delta\sigma_i)^2} \right) / \left(\sum_{i=1}^n \frac{1}{(\Delta\sigma_i)^2} \right) \quad \dots (1)$$

Where the standard deviation error is:

$$S.D. = \frac{1}{\sqrt{\sum_{i=1}^N \frac{1}{(\Delta\sigma_i)^2}}} \quad \dots (2)$$

where σ_i = cross-section. $\Delta\sigma_i$ = corresponding error for each cross-section value.

3.2. Stopping Power

Stopping Power and Range of Ions in Matter (SRIM) is a collection of computer programs that was developed by James F. Ziegler and Jochen P. Biersack in 1983. [11, 12]. PSTAR is a program that calculates stopping power and ranges in tables for protons or deuterons in various materials. It's developed by the National Institute of Standards and Technology.

3.3. Yield

The yield (Y) of product nuclei is displayed as a function of the cross section for any given energy (e) [13]:

$$Y = \frac{N.H}{A} i (1 - e^{-\lambda t}) \int_{e \text{ out}}^{e \text{ in}} \sigma(e) \left(\frac{dE}{\rho dx} \right)^{-1} de \quad \dots (3)$$

where the yield is calculated based on the value of the cross-sections and the stopping power at the same energy, N is Avogadro's number, A is the mass number, H is the abundance of the target, t is the time of radiation, λ is the decay constant for the product, and i is the current.

4. Results and Discussion

We used the experimental results to calculate nuclear reaction cross-sections. Table 1 presents published empirical data for induced reactions specific to the ^{100}Mo and ^{98}Mo targets from the International Atomic Energy Agency's EXFOR library. We assessed the suggested cross-sections for the aforementioned EXFOR library target pieces using MATLAB 2013. Various sources did not provide the same energy range for the reaction, so keep that in mind. For this reason, we defined the

energy range in this study by recalculating the energy increments of 0.01 MeV through interpolation. Figures 1–6 show the plotted results of the computed cross-sections. We calculated the yield using equation (3). We computed stopping power values using the SRIM-2013 and PSTAR codes. We compared the yield values from both codes. The isotope $^{99\text{m}}\text{Tc}$ is used in most medical examinations and on a wide scale, and it can be produced in two ways: either directly through the reactions mentioned in Table 1, as shown in Figures 1, 2, and 3, or indirectly through the decay of the isotope ^{99}Mo into $^{99\text{m}}\text{Tc}$ over 66 hours. Table 1 mentions reactions that can produce the isotope ^{99}Mo , as shown in Figures 4, 5, and 6. The yield calculation was based on the proposed cross-sections and stopping power as described in equation (3), and Figure 7 represents the yield calculations for all reactions.

Table 1. The EXFOR Library's $^{99\text{m}}\text{Tc}$ and ^{99}Mo production reaction features and experimentally available data.

Target	Reactions	Product	Range of energy (MeV)	Author ref. No.
^{100}Mo	(d,3n)	$^{99\text{m}}\text{Tc}$	6.7 - 49.5	[14].
^{98}Mo	(d,n)	$^{99\text{m}}\text{Tc}$	0.8 - 11.3	[15].
			6.05 - 11.75	[16].
^{100}Mo	(p,2n)	$^{99\text{m}}\text{Tc}$	3.3 - 17.3	[7].
			7.2 - 64.8	[17].
			8.01 - 19.07	[18].
			8.12 - 20.85	[19].
			8.38 - 35.54	[20].
			8.5 - 17.5	[21].
			9.54 - 24.6	[22].
^{98}Mo	(d,p)	^{99}Mo	0.8 - 11.3	[23].
			3.4 - 12.7	[23].
			5.57 - 11.78	[16].
^{100}Mo	(d,x)	^{99}Mo	8.55 - 48.71	[24].
			19.1 - 49.5	[14].
^{100}Mo	(p,x)	^{99}Mo	3.3 - 17.3	[7].
			8.01 - 19.07	[18].
			9.8 - 38.6	[25].
			10.58 - 20.85	[19].
			11.43 - 35.54	[20].
			12.61 - 37.9	[26].
			22.34 - 66.58	[27].

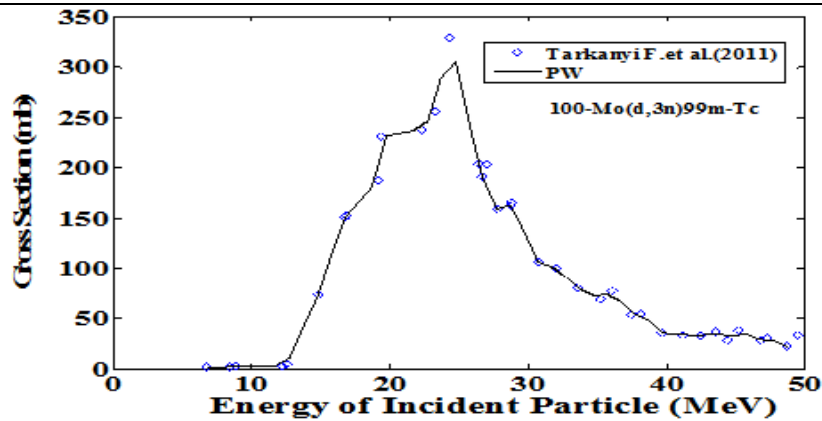


Figure 1. Suggested cross section for $^{100}\text{Mo}(d,3n)^{99m}\text{Tc}$.

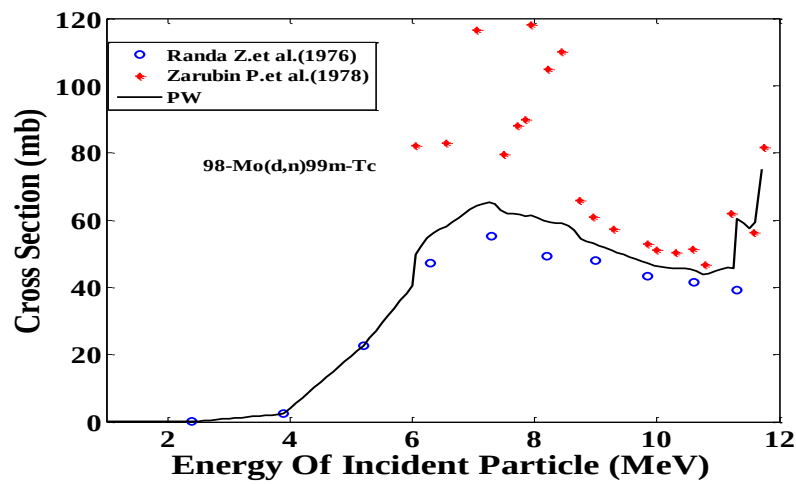


Figure 2. Suggested cross section for $^{98}\text{Mo}(d,n)^{99m}\text{Tc}$.

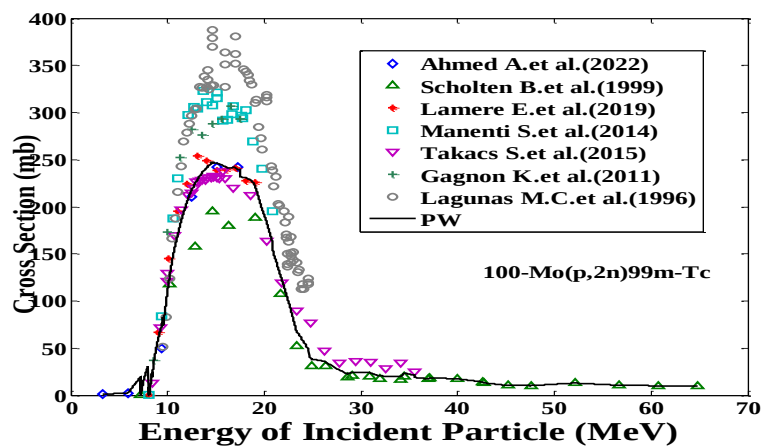


Figure 3. Suggested cross section for $^{100}\text{Mo}(p,2n)^{99m}\text{Tc}$.

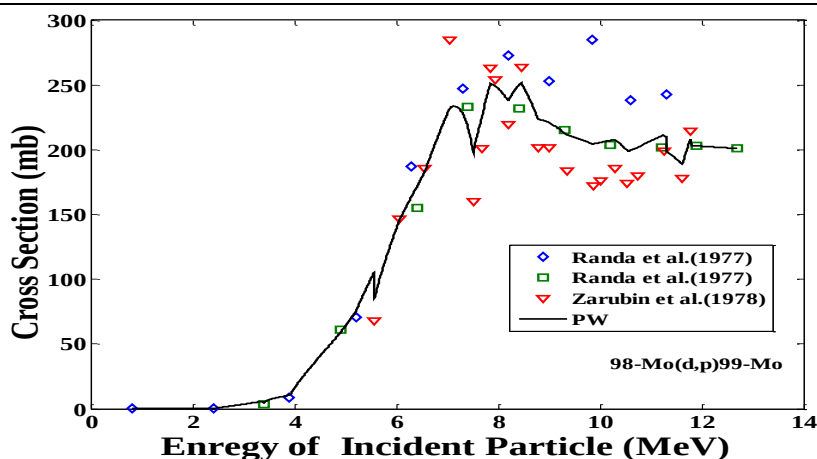


Figure 4. Suggested cross section for $^{98}\text{Mo}(d,p)^{99}\text{Mo}$.

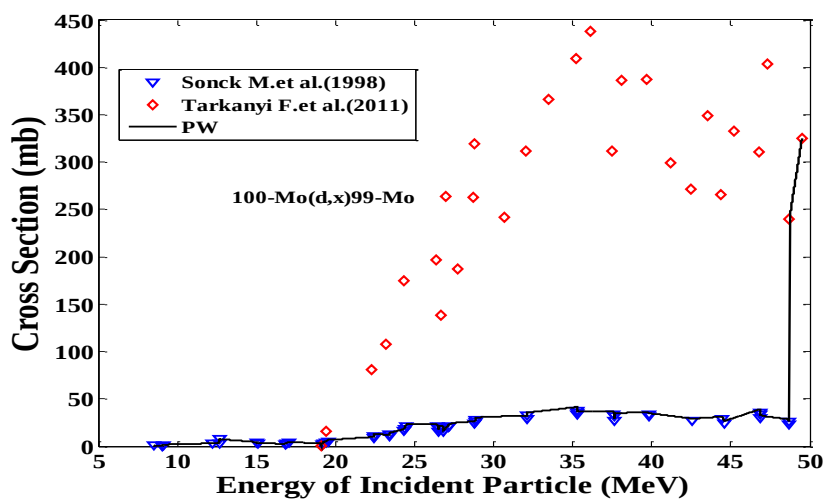


Figure 5. Suggested cross section for $^{100}\text{Mo}(d,x)^{99}\text{Mo}$.

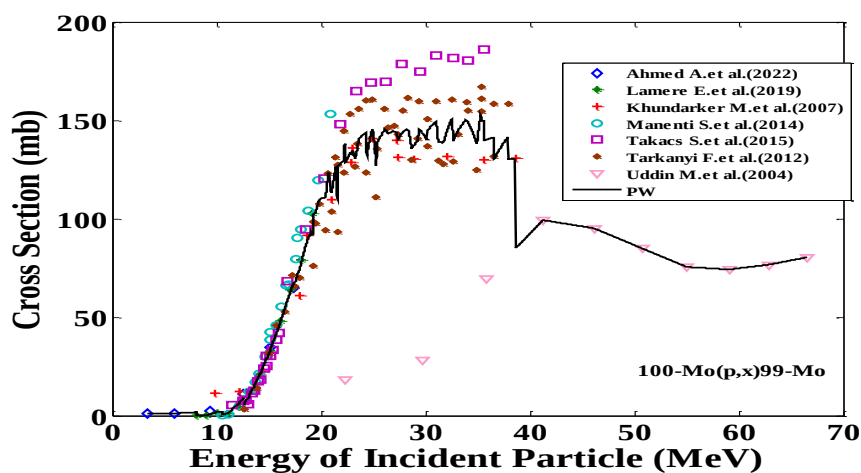
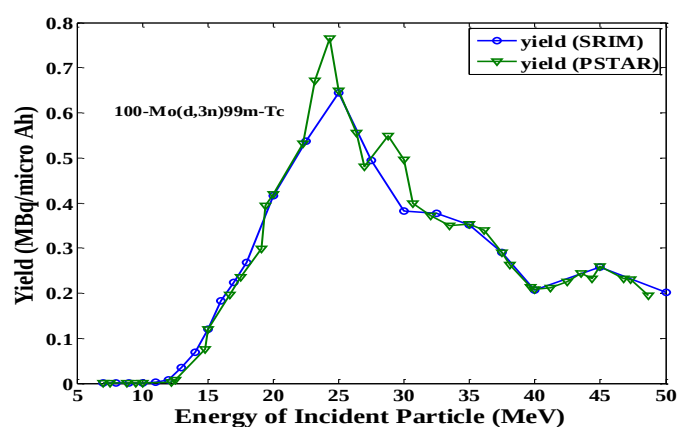
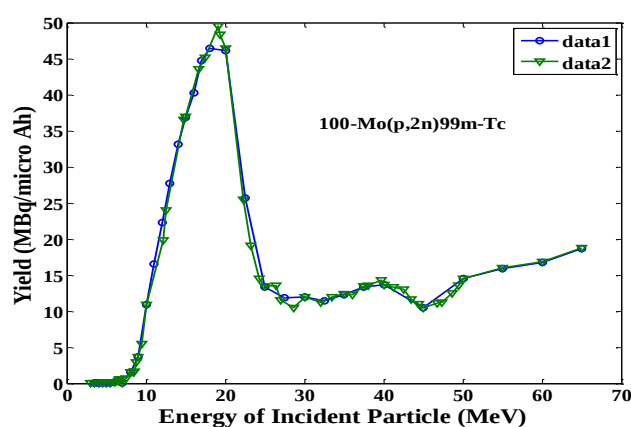


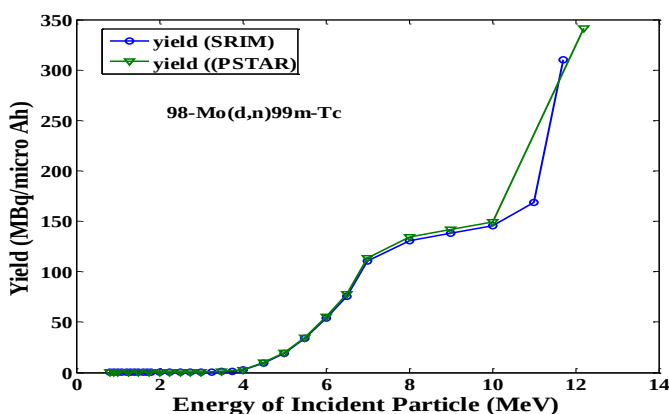
Figure 6. Suggested cross section for $^{100}\text{Mo}(p,x)^{99}\text{Mo}$.



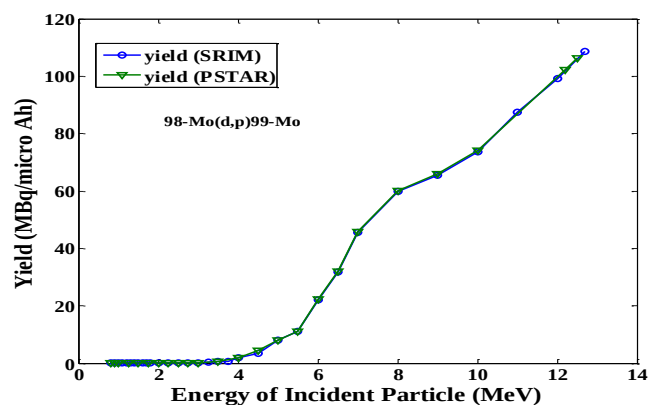
(a) The yield for ^{99m}Tc from $^{100}\text{Mo}(d,3n)^{99m}\text{Tc}$ reaction.



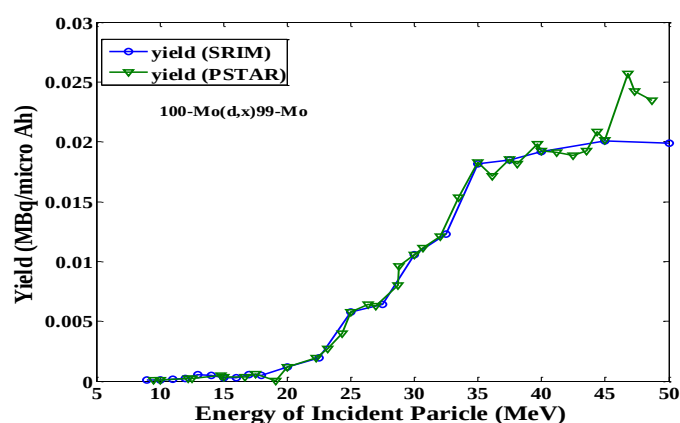
(b) The yield for ^{99m}Tc from $^{100}\text{Mo}(p,2n)^{99m}\text{Tc}$ reaction.



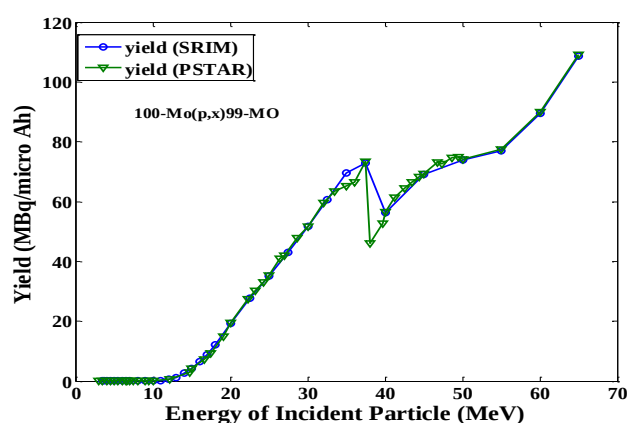
(c) The yield for ^{99m}Tc from $^{98}\text{Mo}(d,n)^{99m}\text{Tc}$ reaction.



(d) The yield for ^{99}Mo from $^{98}\text{Mo}(d,p)^{99}\text{Mo}$ reaction.



(e) The yield for ^{99}Mo from $^{100}\text{Mo}(d,x)^{99}\text{Mo}$ reaction.



(f) The yield for ^{99}Mo from $^{100}\text{Mo}(p,x)^{99}\text{Mo}$ reaction.

Figure 7. (a-c) yield production for ^{99m}Tc (d-f) yield production for ^{99}Mo .

4.1. ^{99m}Tc production cross section

The isotope ^{99m}Tc can be produced through the $^{100}\text{Mo}(d,3n)^{99m}\text{Tc}$ reaction, where the energy range for [14] is (6.7 – 49.5) MeV with the highest cross section of 305 mb at $E_d = 24$ MeV. The calculated yield is $Y1 = 0.643$ MBq/microAh at $E_d = 25$ MeV and $Y2 = 0.764$ MBq/microAh at $E_d = 24.3$ MeV, the radiation time = 0.5 h, and the current beam = 0.04 microA. The $^{98}\text{Mo}(d,n)^{99m}\text{Tc}$ reaction, where the energy range is (0.8 – 11.75) MeV, for [15] and [16], with the highest cross section of (75) mb at $E_d = 11.75$ MeV. The calculated yield is $Y1 = 310$ MBq/microAh at $E_d = 11.7$ MeV and $Y2 = 41$ MBq/microAh at $E_d = 12.2$ MeV, the radiation time is 5 min, and the current beam = 5.3 microA. The $^{100}\text{Mo}(p,2n)^{99m}\text{Tc}$ reaction, where the energy range is (3.3 – 64.8) MeV, for [7,17-22], with the highest cross section of 251.14 mb at $E_p = 14.54$ MeV. With the calculated yield $Y1 = 46.4$ MBq/microAh at $E_p = 18$ MeV, $Y2 = 48.3$ MBq/microAh at $E_p = 19$ MeV, the radiation time = 36 h, and the current beam = 0.7 microA, the above results demonstrate highly convergent values for $Y1$ and $Y2$.

4.2. ^{99}Mo Production Cross Section

The isotope ^{99}Mo can be produced through the $^{98}\text{Mo}(d,p)^{99}\text{Mo}$ reaction, where the energy range is (0.8 – 12.7) MeV, for [23] and [16], with the highest cross section of 244 mb at $E_d = 8.7$ MeV. The calculated yield is $Y1 = 108.6$ MBq/microAh, $E_d = 12.7$ MeV, $Y2 = 106.3$ MBq/microAh, $E_d = 12.5$ MeV, the radiation time = 17.78 h, and the current beam = 3.4 microA. The $^{100}\text{Mo}(d,x)^{99}\text{Mo}$ reaction, where the energy range is (8.5 – 50) MeV, for [24] and [14], with the highest cross section of 41.14 mb at $E_d = 35$ MeV. The calculated yield is $Y1 = 0.02$ MBq/microAh, $E_d = 45$ MeV, $Y2 = 0.025$ MBq/microAh, $E_d = 46.8$ MeV, the radiation time = 0.5 h, and the current beam = 0.04 microA. The $^{100}\text{Mo}(p,x)^{99}\text{Mo}$ reaction, where the energy range is (3.3 – 66.85) MeV for [7, 18,19, 20, 25, 26, and 27], with the highest cross section of 149 mb at $E_p = 35.3$ MeV. The calculated yield is $Y1 = 108$ MBq/microAh at $E_p = 65$ MeV and $Y2 = 109$ MBq/microAh at $E_p = 65$ MeV, the radiation time = 36 h, and the current beam = 0.7 microA. The aforementioned results indicate a strong convergence between $Y1$ and $Y2$ values.

5. Conclusions

Medical procedures in nuclear medicine, such as diagnosis and treatment, largely rely on the technetium-99m isotope, giving it significant importance in this field. Recently, researchers have faced challenges in producing this isotope, mainly

due to some nuclear reactors reaching the end of their lifespan or being decommissioned. Therefore, alternatives must be found to compensate for the potential shortages. The synthesis of the medicinal isotope ^{99m}Tc and its parent ^{99}Mo using charged particles such as protons and deuterons on ^{100}Mo and ^{98}Mo yielded varying results among the reactions employed. The results showed that (d,p) and (d,n) reactions have a promising future in the production of ^{99m}Tc and ^{99}Mo , demonstrating good agreement with previous experimental studies. It is worth noting that the proton-induced reactions have shown very good results with high cross sections and good yields within the medium energy range for both reactions (p,2n) and (p,x), considered good alternatives for the production of both ^{99}Mo and ^{99m}Tc . Radioisotopes (^{99}Mo , ^{99m}Tc) must be handled with caution, using protective shields, isolated rooms, and dosimetry devices. We suggest that researchers pay more attention to deuteron-induced reactions on molybdenum for the synthesis of the crucial medical technetium-99m isotope and use molybdenum-enriched rather than natural molybdenum. Further studies: Study the possibility of producing ^{99}Mo from the neutron irradiation of ^{98}Mo using commercial reactors.

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