Spectral Analysis of Proton-Irradiated Natural MoO_3 Relevant for Technetium-99m Radionuclide Production

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Abstract. Due to the declining number of available nuclear reactors capable of Tc-99m production and tight regulations related to uranium enrichment, cyclotron-based Tc-99m production has recently been suggested as a new method to help ease Tc-99m supply shortages. In this investigation, a solid natural MoO_3 target was irradiated using 11-MeV proton beams at variable proton doses. The proton doses were varied by varying the irradiation time while keeping the proton beam current constant at 20 μA. At the end of the bombardment, the post-irradiated solid MoO_3 targets were analyzed for their radioactive contents using a portable gamma ray spectroscopy system. The analysis was also performed for the post-irradiated targets after dissolving the solid MoO_3 in a 6M NaOH solution. The experimental results indicated that as much as 75.71% of Tc-99m radioactivity was directly generated via a $^{100}Mo(p,2n)^{99m}Tc$ nuclear reaction, while the rest of the Tc-99m radioactivity was a result of a $^{98}Mo(n,\gamma)^{99}Mo \rightarrow ^{99m}Tc$ nuclear reaction. Apart from Tc-99m and Mo-99 radionuclides, some other radionuclides such as N-13, Tc-96 and Nb-96 were also recorded following temporal observation of the NaOH-dissolved MoO_3. These experimental results open up the possibility of direct production of Tc-99m using a proton-accelerating cyclotron.

Keywords: *cyclotron; Mo-99; MoO_3 target; proton; Tc-99m production.*

1 Introduction

Proton beams accelerated in cyclotrons have been employed to study material erosion [1] as well as to produce medical radionuclides such as F-18 [2], Cu-64 [3], Tc-94m [4], etc. One of the most important radioisotopes applied in nuclear medicine procedures is Tc-99m, which emits gamma rays at 140 keV and decays at a half-life of 6 hours. The relatively low gamma ray energy and short half-life make Tc-99m suitable as a radioactive tracer for medical diagnostic

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procedures by means of Single Photon Emission Computed Tomography (SPECT) modality. The most widely applicable technique for Tc-99m production is by bombarding natural molybdenum targets consisting of Mo-98 atoms using neutrons generated from nuclear reactors via a $^{98}Mo(n,\gamma)^{99}Mo \rightarrow ^{99m}Tc$ nuclear reaction. The direct result of the bombardment is Mo-99, which immediately decays into Tc-99m; thus, an Mo-99/Tc-99m generator is required for extracting Tc-99m properly to meet radiochemical purity requirements. Nevertheless, due to the declining number of available nuclear reactors capable of such production and tight regulations related to uranium enrichment, reports on Tc-99m supply shortages have emerged [5-6]. The supply shortages have caused the price of Mo-99/Tc-99m generators to soar. A new method of cyclotron-based Tc-99m production has therefore been proposed to tackle these Tc-99m supply shortages [7-8].

Recent theoretical calculations [9] suggest that as much as 42.18 GBq/uA.hr can be produced from 11-MeV proton irradiation of enriched ^{100}Mo targets at the end of bombardment, while experimental studies highlighted the possibility of generating high yields of Tc-99m using medium- and high-energy cyclotrons [10-11]. Nevertheless, no reports have been published on the commercial use of cyclotron-based Tc-99m radionuclide due to the low Tc-99m yield as well as radionuclide impurities produced during bombardment.

Gaining a better understanding of all radionuclides produced during proton irradiation of molybdenum targets is therefore of paramount importance. In this experimental study, the temporal evolution of the post-irradiated MoO_3 spectrum was evaluated in order to observe changes in the presence of all produced radionuclides. Furthermore, in this paper we only concentrated on the analysis of the Tc-99 spectra produced from an 11-MeV proton bombardment. Further studies, particularly on the produced Tc-99m in the form of pertechnetate, Tc O4 (including its practical use), will be discussed in another paper. To the best of the authors' knowledge, there no publication has yet reported a detailed spectral analysis of the produced Tc-99m and the impurities following 50 days of irradiation. The outcomes of this research are useful for Tc-99m production as well as for safety concerns regarding long-lived radionuclides. In addition, no Tc-99m has previously been produced using an 11-MeV cyclotron.

2 Experimental Set-up

2.1 Target Preparations

As much as 1.1 gram MoO_3 powder (purchased from Sigma-Aldrich Germany) was pressed into a solid disk of 1.8 cm in diameter and 0.3 cm thick using a 30-

N hydraulic presser. The solid MoO_3 target was then heated in a furnace at a constant temperature of 600 °C for 3 hours to remove vapors and other possible watery impurities. The final product of this target preparation was a clear white disk of MoO_3. In this experiment, the natural molybdenum consisted of several Mo atoms, including Mo-92 (14.84%), Mo-94 (9.25%), Mo-95 (15.92%), Mo-96 (16.68%), Mo-97 (9.55%), Mo-98 (24.13%), and Mo-100 (9.63%).

2.2 Target Irradiation

The disk target of MoO_3 was placed in an aluminum-based target holder so that the proton beam would hit the target perpendicularly during irradiation of the target, which was performed using an 11 MeV cyclotron at Dharmais Cancer Hospital in Jakarta. The 11 MeV proton beams bombarded the MoO_3 target at a constant beam current of 20 μA. During the bombardment, the proton dose was varied by varying the irradiation time from 2 minutes to 5 minutes, resulting in proton doses between 0.67 and 1.67 μAh. The general proton irradiation procedure was performed using an 11 MeV cyclotron has been discussed previously in [12].

2.3 Target Dissolving

The post-irradiated MoO_3 target was dissolved in a solvent containing 6M NaOH, followed by mixing the solution using a magnetic stirrer at a speed of 1000 rpm for 15 minutes. The final solution after dissolving was visibly clear.

2.4 Target Analysis

The radioactivities of the solid MoO_3 as well as the NaOH-dissolved MoO_3 target were measured using a portable gamma ray spectroscopy system, which had been described elsewhere [12-13]. The measurement was performed by sampling 10 μL of the NaOH-dissolved MoO_3 solution for a counting time of 5 minutes for each sample, and each spectrum was analyzed after background subtraction. For radioactive impurity measurement, gamma ray detection was carried out from 2 hours after the end of bombardment (EOB) to 50 days after the EOB to obtain the temporal evolution of the NaOH-dissolved MoO_3 spectrum.

3 Results and Discussion

3.1 Spectral Analysis of Post-Irradiated MoO_3

The gamma ray spectrum of the proton-irradiated solid MoO_3 target observed 2 hours after the end of the bombardment is shown in Figure 1, which indicates that apart from the intensity, there was no significant difference in the energy of

the gamma rays recorded for two different proton doses (0.67 and 1.67 μAh). The relatively strong gamma rays at 0.181 MeV correspond to the Mo-99 peak. Two possible nuclear reactions for Mo-99 production in this experiment can be explained as follows:

1. Direct Mo-99 production via $^{100}Mo(p,d)^{99}Mo$ nuclear reactions. According to the TALYS code calculations performed previously [9], while the proton threshold energy for such a nuclear reaction to occur is only 6.1 MeV, this typical nuclear reaction is very likely undetectable due to very low nuclear cross-section at the 11 MeV proton beam, which is theoretically only 7.5×10^{-3} mbarn. The presence of a $^{100}Mo(p,d)^{99}Mo$ nuclear reaction has been suggested by Lebeda and co-workers [14] since they employed 18-MeV proton beams in their investigation. For 18-MeV proton beams, the nuclear cross-section is theoretically 107.6 mbarn, which potentially causes a $^{100}Mo(p,d)^{99}Mo$ nuclear reaction to occur.

2. Since secondary neutrons are also generated during the proton bombardment of the MoO_3 target, Mo-99 could also potentially be produced via a $^{98}Mo(n,\gamma)^{99}Mo$ nuclear reaction. Again, based on the TALYS calculated results [9], such a nuclear reaction is very likely to occur due to high nuclear cross-sections for slow to fast neutrons. Thus the most possible nuclear reaction for Mo-99 generation in this experiment was $^{98}Mo(n,\gamma)^{99}Mo$.

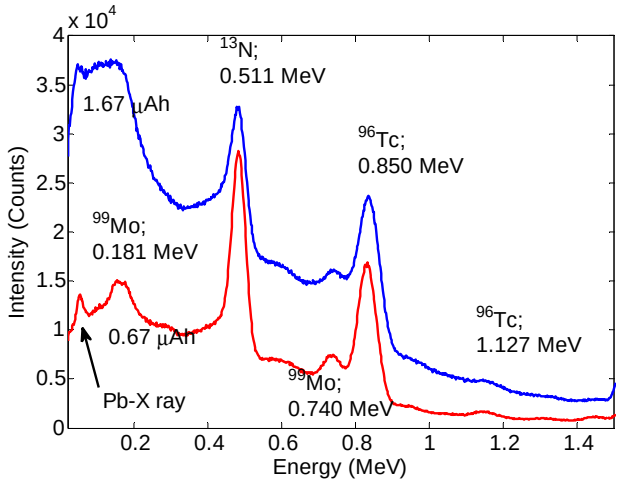

Figure 1 The gamma ray spectrum of the proton-irradiated solid MoO_3 after 2 hours of decay for proton doses of 0.67 (red line) and 1.67 μAh (blue line).

Another pronounced peak, at 0.511 MeV, is presumably due to gamma rays emitted by nitrogen-13 (N-13) radionuclide. The presence of N-13 relates to the oxygen-16 (O-16) content in the MoO_3 target, which undergoes a $^{16}O(p,\alpha)^{13}N$

nuclear reaction when proton beams hit the target. The unstable N-13 emits positron (β^+) particles that immediately interact with free electrons around them and then are annihilated by emitting gamma rays at 0.511 MeV. With a half-life of 9.97 minutes, the N-13 impurity is expected to vanish after a few hours decay.

Also in Figure 1, slightly weak intensity can be observed at 0.739 MeV, which is emitted by Mo-99, while the very strong peak at 0.850 MeV is presumably due to Tc-96 radionuclide following ^{96}Mo(p,n)^{96}Tc and ^{97}Mo(p,2n)^{96}Tc nuclear reactions. Both nuclear reactions are possible since their threshold energies are 3.830 MeV for the ^{96}Mo(p,n)^{96}Tc reaction and 10.687 MeV for the ^{97}Mo(p,2n)^{96}Tc reaction, respectively. The identified Tc-96 is also supported by the weak gamma ray intensity at 1.127 MeV. This result agrees with previous theoretical calculations [9] and a previous experimental investigation [14]. Note that at this point, Tc-99m is weakly detected due mostly to self absorption of the emitted gamma ray by the solid MoO_3.

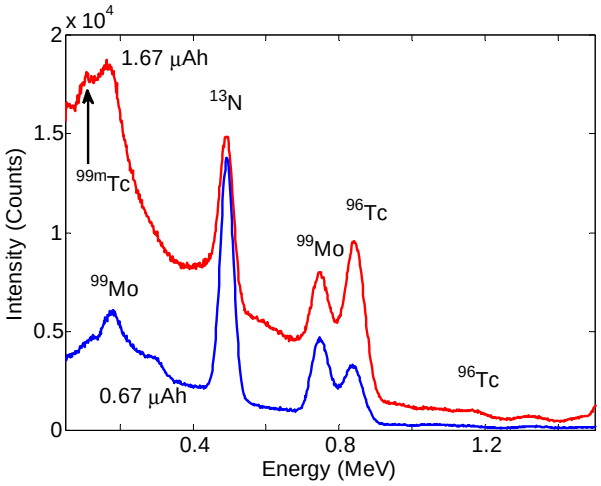

Figure 2 The gamma ray spectrum of the NaOH-dissolved MoO_3 after 2 hours of decay for proton doses of 0.67 and 1.67 μAh.

Compared to the solid MoO_3 spectrum, there was a slight difference in the types of radionuclides detected in the NaOH-dissolved MoO_3, particularly the presence of the Tc-99m spectrum at 0.140 MeV, as can be seen in Figure 2. Moreover, the intensities of Mo-99 at 0.181 and 0.740 MeV looked more pronounced in the solution. Self absorption of Mo-99 gamma rays clearly occurred in the solid MoO_3, resulting in lowering Mo-99 intensity before the post-irradiated target was dissolved in the NaOH solution. Another interesting feature is that the Tc-96 intensity was higher with increasing proton dose.

At a proton dose of 1.67 μAh, as much as 0.84 ± 0.05 μCi of Tc-99m was recorded 2 hours after the EOB, while 0.87 ± 0.04 μCi of Mo-99 was detected at the same time. The almost identical amounts of Mo-99 and Tc-99m radioactivity observed in the experiment indicate that the Tc-99m measured comes from both Mo-99 decay as a result of a $^{98}Mo(n,\gamma)^{99}Mo \rightarrow ^{99m}Tc$ nuclear reaction and direct production of Tc-99m via a $^{100}Mo(p,2n)^{99m}Tc$ nuclear reaction.

According to the Mo-99/Tc-99m equilibrium equation, the radioactivity ratio of daughter radionuclide (A_d) and parent radionuclide (A_p) depends on the decay constants of the daughter (λ_d) and the parent (λ_p), which can be calculated as follows:

$$\frac{A_d}{A_p} = \frac{\lambda_d}{\lambda_d - \lambda_p}\left(1 - e^{-(\lambda_d - \lambda_p)t}\right), \quad (1)$$

where t is the decay time.

In the case of Mo-99/Tc-99m, by substituting λ_d = 0.1155 hour^{-1}, λ_p= 0.0105 hour^{-1}, and t = 2 hours, one can immediately obtain that the radioactivity ratio of Tc-99m to Mo-99 as a result of Mo-99 decay is theoretically 20.84%. However, the experimental ratio was found to be 96.55%, which indicates that the majority of the Tc-99m (75.71%) generated in the experiment reported here was due to direct production of Tc-99m via a $^{100}Mo(p,2n)^{99m}Tc$ nuclear reaction.

3.2 Temporal Evolution of MoO_3 Spectrum

In order to better understand the produced Tc-99m and the radionuclidic impurities in the NaOH-dissolved MoO_3, careful observations were carried out from day 1 to 50 after the end of the bombardment. The recorded spectra are shown in Figure 3 and 4, which surprisingly indicate significant amounts of another radionuclidic impurity not observed shortly after the EOB. As can be seen in Figure 3, the remaining radionuclides detected in the NaOH-dissolved MoO_3 solution were dominated by Mo-99 over weaker intensity of Tc-96. As predicted earlier, N-13 radionuclide was no longer observed after 1 day of decay since its half-life is 9.97 minutes.

The new radionuclidic impurity discovered in this investigation was Nb-96, which gave rise to the pronounced peak at 0.569 MeV, as shown in Figure 4. The Nb-96 peak emerged as a result of lower background radiation after several days of decay. The presence of Nb-96 (half-life = 23.35 hours) in this experiment agrees with previous investigation [14], which is possibly due to $^{97}Mo(p,2p)^{96}Nb$ (threshold energy = 9.321 MeV), $^{98}Mo(p,He\text{-}3)^{96}Nb$ (threshold

energy = 8.488 MeV), and ^{100}Mo(p,αn)^{96}Nb nuclear reactions (threshold energy = 3.575 MeV).

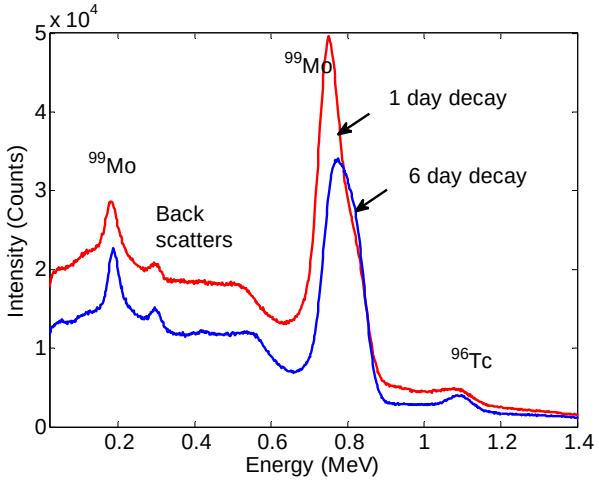

Figure 3 The gamma ray spectrum of the NaOH-dissolved MoO_3 after 1 day and 6 days of decay.

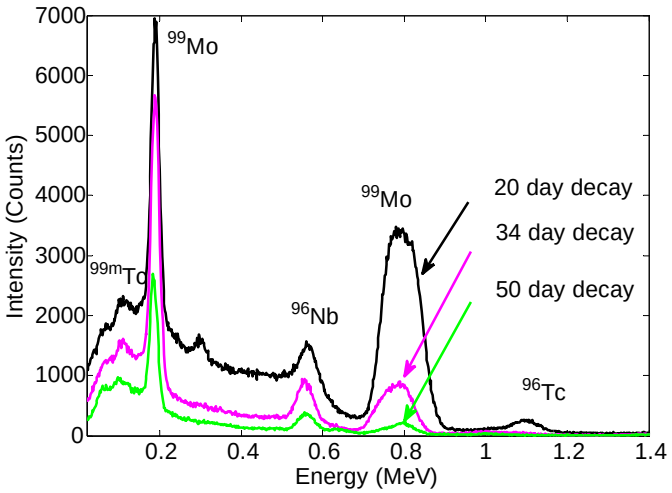

Figure 4 The gamma ray spectrum of the NaOH-dissolved MoO_3 after 20, 34 and 50 days of decay.

After radioactive decay of over 20 days, 4 radionuclides (Tc-99m, Mo-99, Nb-96 and Tc-96) were detected in the NaOH-dissolved MoO_3 solution, while N-13 had completely decayed, as can be seen in Figure 3. Details of the observed radionuclides following a 2-hour to 50-day cooling period of the NaOH-dissolved MoO_3 target is given in Table 1.

Table 1 Radionuclides recorded from proton-irradiated MoO_3 following 2 hours to 50 days of decay.

Radionuclide	Gamma energy (MeV)	Half-life	Nuclear reaction	Threshold energy (MeV)
Tc-99m	0.140	6 h	$^{100}Mo(p,2n)^{99m}Tc$	7.793
Mo-99	0.141 0.181 0.740	65.95 h	$^{98}Mo(n,\gamma)^{99}Mo$	6.126
N-13	0.511	9.97 m	$^{16}O(p,\alpha)^{13}N$	5.547
Tc-96	0.850 1.127	4.28 d	$^{96}Mo(p,n)^{96}Tc$; $^{97}Mo(p,2n)^{96}Tc$	3.795 10.687
Nb-96	0.596	23.35 h	$^{97}Mo(p,2p)^{96}Nb$; $^{98}Mo(p,He\text{-}3)^{96}Nb$; $^{100}Mo(p,\alpha n)^{96}Nb$	9.322 10.255 3.828

According to Polatom, the price of an imported Mo-99/Tc-99 generator is Rp 32 million (USD 2,265) for 400 mCi or Rp 80,000 (USD 57) per mCi. If it is produced locally at Dharmais Cancer Hospital in Jakarta it would cost Rp 37,500 (USD 2.65) per mCi. In order to produce a more competitive Tc-99m supply it is recommended that Tc-99m is locally produced using a cyclotron since the price of a new cyclotron is much lower than that of a new nuclear reactor. In addition, the new cyclotron should be a medium energy cyclotron (15-30 MeV).

4 Conclusion

Experimental production of Mo-99/Tc-99m radionuclide was carried out by bombarding a solid MoO_3 target with 11-MeV proton beams at variable proton beam currents. Using a portable gamma ray spectroscopy system, several radionuclides were detected, i.e. Tc-99m, Mo-99, N-13, Tc-96 and Nb-96. Due to the short half-life of only 9.97 minutes, the N-13 radionuclide decayed completely after a cooling period of 1 day, while the other radionuclides were still observed after 50 days of decay. The experimental data also indicate that nearly 75.71% of the Tc-99m detected in this experiment were a result of direct production of Tc-99m via a $^{100}Mo(p,2n)^{99m}Tc$ nuclear reaction, while the rest of the Tc-99m radioactivity came from a $^{98}Mo(n,\gamma)^{99}Mo \rightarrow ^{99m}Tc$ nuclear reaction. Instead of irradiating a natural Mo target, future research is suggested to use enriched ^{100}Mo target for a higher Tc-99m yield as well as reducing the number of radioactive impurities.

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