Cyclotron-Based Samarium-153 Production Using Alpha Particle Beam Irradiation

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Abstract. Since the demand of samarium-153 (\(^{153}\text{Sm}\)) radioisotope has increased and the reactor-based production capacity has been decreasing over the past few years, researchers have suggested a novel method of \(^{153}\text{Sm}\) production using cyclotrons. In this work, cyclotron-based \(^{153}\text{Sm}\) production using alpha particle beam bombardment through \(^{150}\text{Nd}(\alpha,n)^{153}\text{Sm}\) nuclear reaction is highlighted. Theoretical calculation of the end-of-bombardment (EOB) yield was performed using Matlab code following calculations of its excitation function using the TALYS code. According to the TALYS code calculation, the threshold energy for \(^{153}\text{Sm}\) production was 6.96 MeV, whereas the maximum cross-section (7.88 mbarn) occurred at alpha incident energy of 16 MeV. The calculated EOB yield for \(^{150}\text{Nd}(\alpha,n)^{153}\text{Sm}\) nuclear reaction was found to be 0.032 MBq/\(\mu\)Ah, which was relatively low for such a typical radionuclide production. However, simulated result indicated that high radioactivity of 3200 MBq could be generated when \(^{150}\text{Nd}\) target was irradiated with 50 MeV-alpha beam at an alpha dose of 100,000 \(\mu\)Ah. Such a high radioactivity would be sufficient for palliative therapy. Furthermore, there were three possible radionuclidic impurities such as \(^{153}\text{Pm}\), \(^{152}\text{Pm}\) and \(^{151}\text{Pm}\) predicted to be present during the alpha bombardment.

Keywords: alpha beam, cyclotron, EOB yield, Sm-153, TALYS code

1. Introduction
Samarium-153 (\(^{153}\text{Sm}\)) radioisotope has been currently applied for treatment of painful bone metastases [1], though external radiation therapy could also be employed for bone pain palliation [2]. As a beta emitting radioisotope and with a half life of 46.28 hours, \(^{153}\text{Sm}\) could immediately be of paramount interest in nuclear medicine procedures. Previous reports on treatment of bone pain in patients with metastatic prostate cancer [3-5], breast cancer and other malignancies [6] have shown positive responses to the treatment. Other reports on use of \(^{153}\text{Sm}\) can be found elsewhere [7-15]

The growing demand for radiopharmaceuticals, including \(^{153}\text{Sm}\)-labeled radiopharmaceuticals has been of a concern since the supply of \(^{153}\text{Sm}\) radioisotope is very limited. More importantly, production of \(^{153}\text{Sm}\) has been extremely dependent on the available nuclear reactors. In addition, the number of installed nuclear reactors with such a capacity has remained constant. Therefore new methods for \(^{153}\text{Sm}\) production are required to tackle the \(^{153}\text{Sm}\) shortage.

There have been very limited references on alternative production of \(^{153}\text{Sm}\) elsewhere, though recent studies suggested alpha particles which are accelerated using powerful cyclotrons or accelerators. Preliminary investigation on excitation function of \(^{150}\text{Nd}(\alpha,n)^{153}\text{Sm}\) nuclear reaction [16] indicated that there was a great possibility of producing \(^{153}\text{Sm}\) using the proposed route, though to the best of our knowledge such a pathway has not been discussed further elsewhere. Moreover, cyclotrons and accelerators have been previously employed to produce radioisotope [17-18] and material studies [19-21]
In this work $^{153}$Sm production aspects through $^{150}$Nd($\alpha$,n)$^{153}$Sm nuclear reaction are theoretically discussed, including its nuclear cross-section, end-of-bombardment (EOB) yield, as well as dependence of alpha beam dose on the $^{153}$Sm radioactivity yield.

2. Materials and Methods

In this study, alpha particles ranging from 0 to 70 MeV were simulated using the two common software applicable for radioisotope production and ion beam analysis, namely – the Stopping and Range of Ions in Matters (SRIM 2013) [22] and TALYS [23] codes. The SRIM (version 2013) was used to calculate the range of alpha particle in the target of interest ($^{150}$Nd). The calculation procedures were similar to the previous published work [24-27], though some changes to the irradiation parameters were performed due to different targets and radioisotopes produced in each published literatures.

The TALYS code calculation performed for the excitation function of $^{150}$Nd($\alpha$,n)$^{153}$Sm nuclear reaction was the latest version of TALYS-Evaluated Nuclear Data Library (TENDL 2017). Eventually the end-of-bombardment (EOB) yield was calculated by developing a Matlab code-based calculation. Furthermore the dependence of alpha beam energy, beam current and irradiation time on the produced radioactivity yield was simulated for the available IBA cyclone 70 which is capable of accelerating up to 70-MeV alpha beams at a maximum beam current of 28.

![Figure 1. Comparison of TALYS-calculated nuclear cross-sections for $^{150}$Nd($\alpha$,n)$^{153}$Sm nuclear reaction (this work, blue circles) and earlier published work by Tárkányi et al [29] (black line)](image1)

![Figure 2. Calculated EOB yields of $^{150}$Nd($\alpha$,n)$^{153}$Sm nuclear reaction in the alpha energy range between 0 and 70 MeV)](image2)

3. Results and Discussion

3.1 Energy Dependence of Nuclear Cross-sections and EOB yield

Cyclotron-based production of $^{153}$Sm requires enriched $^{150}$Nd target to be irradiated using alpha particle beams. The SRIM calculations show that the target thickness should be around 50 $\mu$m when it is bombarded with 10-MeV alpha particles, whereas it should be made thicker (up to 620 $\mu$m) when 50-MeV alpha beams are employed in the irradiation. According to the TALYS calculations, the $^{150}$Nd($\alpha$,n)$^{153}$Sm nuclear cross-sections is greatly dependant on the incoming alpha particle energy. At low alpha energy, the cross-section increases dramatically with increasing energy, but then it goes down with increasing energy when the incoming particle is greater than 17 MeV as can be seen in Figure 1. As well, the threshold energy of the $^{150}$Nd($\alpha$,n)$^{153}$Sm reaction is 6.96 MeV, whereas the
maximum cross-section is 7.88 mbarn which occurs at alpha incident energy of 16 MeV. Comparison with previously published work [16] indicates that the calculated results are in good agreement with it (Figure 1).

As depicted in Figure 2, in the alpha energy range between 0 and 70 MeV, the calculated EOB yield shows increasing yield values, particularly for alpha energy lower than 45 MeV. The radioactivity yield slowly decreases for alpha energy greater than 45 MeV. Nevertheless the maximum yield is only 0.032089 MBq/µAh at alpha energy of 45 MeV, which is relatively low for typical radionuclide production.

3.2 Effects of target thickness, beam current and irradiation time

As can be seen in Figure 3, 150Nd target thickness is extremely important prior to irradiation since the radioactivity yield is dependence on the prepared thickness. However, in general there is no significant difference in the yield when the target thickness is thicker than 500 µm due to the yield saturation. A maximum yield of 12.8 MBq is generated when a 400-µAh alpha beam is irradiated into a 500-µm thick 150Nd target. In Figure 4, while the energy of alpha particle (between 50 and 70 MeV) would not give rise to the radioactivity yield, the yield for different beam currents remains increasing, i.e at 50 µA beam current and 40 MeV.

Prolonged irradiation time could contribute to the high radioactivity yield applicable for palliative therapy. For example, at 20 µA if one increases the duration of the bombardment from 2,000 hours to 100,000 hours the yields would go from 2053 MBq to 65718 MBq which are sufficient for palliative therapy purposes (Figure 5), though such prolonged irradiation time would be technically difficult. Nevertheless, it remains possible as long as stable alpha beam can be maintained during its acceleration in cyclotron. Furthermore the simulated result indicates that high radioactivity of 3200 MBq could be generated when 150Nd target was irradiated with 50 MeV-alpha beam at an alpha dose of 100,000 µAh. It should also be noted that all beam current shows similar trend regarding the yield dependence of the irradiation time.

![Figure 3](image3.jpg)  ![Figure 4](image4.jpg)

Figure 3. Target thickness dependence of EOB yield for several alpha beam doses  Figure 4. Alpha beam current dependence on the EOB yield
3.3 Possible impurities

Other nuclear reactions could possibly occur during alpha beam irradiation of the enriched $^{150}$Nd target. Thus the amount of generated impurities is greatly influenced by the possible nuclear reactions as can be predicted from their excitation functions. Based on the TALYS calculated results, there are three possible nuclear reactions involving the incoming alpha beams, namely $(\alpha,p)$, $(\alpha,t)$ and $(\alpha,d)$ reactions whose nuclear cross-sections are significantly high as shown in Figure 6. It can be seen that the by-products would be present in the post irradiated $^{150}$Nd target when the target is bombarded with any alpha beams greater than 15 MeV since the threshold energies for the three $(\alpha,p)$, $(\alpha,t)$ and $(\alpha,d)$ reactions are 8.11 MeV, 13.16 MeV and 13.49 MeV respectively. As well, among the three possible nuclear reactions, $(\alpha,t)$ has the highest cross-section.

The expected radionuclidic impurities are listed in Table 1, which indicates that all predicted impurities such as $^{153}$Pm, $^{152}$Pm and $^{151}$Pm radioisotopes emit beta particles with half-lives ranging from as short as 5.25 minutes for $^{153}$Pm to as long as 28.40 hours for $^{151}$Pm. While the two impurities
(\(^{153}\)Pm and \(^{152}\)Pm) might not be of a great safety concern due to their short half-lives, the other impurity (\(^{151}\)Pm) must be well taken care of.

Table 1. Various impurities predicted during production of \(^{153}\)Sm radionuclide production

| Isotopes of Pm | Nuclear reaction | Threshold energy (MeV) | Decay mode | Half life |
|---------------|------------------|------------------------|------------|----------|
| \(^{153}\)Pm   | \(^{150}\)Nd(α,p)\(^{153}\)Pm | 8.11                  | β          | 5.25 min |
| \(^{152}\)Pm   | \(^{150}\)Nd(α,τ)\(^{152}\)Pm | 13.16                 | β          | 4.12 min |
| \(^{151}\)Pm   | \(^{150}\)Nd (α,d)\(^{151}\)Pm | 13.49                 | β          | 28.40 h  |

4. Conclusion

Cyclotron-based \(^{153}\)Sm production has been theoretically studied using the SRIM and TALYS codes. In this work, alpha particle is suggested to irradiate \(^{150}\)Nd target to generate \(^{153}\)Sm through \(^{150}\)Nd(α,n)\(^{153}\)Sm nuclear reaction. The TALYS calculated results indicate that the \(^{153}\)Sm radioactivity yield is extremely dependent on the incoming alpha energy. Moreover, it is also influenced by the other irradiation parameters such as the target thickness, alpha beam current and irradiation time. Prolonged irradiation time is required to produce significant level of \(^{153}\)Sm applicable for palliative therapy. For instance, one could generate 3200 MBq of \(^{153}\)Sm when the enriched \(^{150}\)Nd target was irradiated with 50-MeV alpha beam at an alpha dose of 100,000 µAh. Furthermore, based on the TALYS calculations, there are three possible beta emitting radionuclides such as \(^{153}\)Pm, \(^{152}\)Pm and \(^{151}\)Pm which could be present as impurities during the alpha bombardment.

Acknowledgements

The author would like to acknowledge funding from The Indonesian National Nuclear Energy Agency (BATAN). Discussion with researchers and staff of the Center for Radioisotope and Radiopharmaceutical Technology, BATAN is also gratefully acknowledged.

References

[1] Sartor O 2004 Rev. Urol. 6 S3
[2] Shiloh R, Krishnan M 2018 Hematology/Oncology Clinics of North America 32 459
[3] Bączyk M, Milecki P, Martenka P, Sowiński J 2007 Reports of Practical Oncology & Radiotherapy 12 211
[4] Petersen LJ, Lund L, Jønler M, Jakobsen M, Abrahamsen J 2010 Dan. Med. Bull. 57 A4154
[5] Valicenti RK, Pugh SL, Trabulsi EJ, Sartor O, Ko EC, Girvigian MR, Rosenthal SA, Shaves ME, Hoffman-Censits JH, Schallenkamp J, Sandler HM 2018 International Journal of Radiation Oncology Biology Physics 100 695
[6] Correa-González L, Murphy CA, Pichardo-Romero P, Pedraza-López M, Moreno-García C, Correa-Hernández L 2014 Archives of Medical Research 45 301
[7] Body JJ, Quinn G, Talbot S, Booth E, Demonty G, Taylor A, Amelio J 2017 Critical Reviews in Oncology/Hematology 115 67
[8] Prior JO, Gillessen S, Wirth M, Dale W, Aapro M, Oyen WJG 2017 European Journal of Cancer 77 127
[9] Kalef-Ezra JA, Valakis ST, Pallada S 2015 Physica Medica 31 104
[10] Liberal FDCG, Tavares AAS, Tavares JMRS 2016 Appl. Radiat. Isot. 110 87
[11] Valicenti RK, Trabulsi E, CharlesIntenzo C, JorosaliLavarino J, Xu Y, Chervoneva I 2011 *International Journal of Radiation Oncology Biology Physics* 79 4732
[12] Paravati AJ, Russo AL, Aitken C 2011 *International Journal of Radiation Oncology Biology Physics* 81 506
[13] Abbasian P, Foroghy M, Jalilian AR, Hakimi A, Shirvani-Arani S 2014 *Reports of Practical Oncology & Radiotherapy* 19 214
[14] Essman SC, Lewis MR, Fox DB 2008 *Nucl. Med. Biol.* 35 219
[15] Russo AL, Paravarti AJ, Aitken CL 2009 *International Journal of Radiation Oncology Biology Physics* 75 S115
[16] Tárkányi F, Hermanne A, Takács S, Ditrói F, Csikai J, Ignatyuk AV 2014 *Appl. Radiat. Isot.* 91 31
[17] Kambali I, Parwanto, Suryanto H, Huda N, Listiawadi FD, Astarina H, Ismuha RR, Kardinah 2017 *Physics Research International* 2017 1
[18] Kambali I, Suryanto H, Parwanto 2016 *Australas. Phys. Eng. Sci. Med.* 39 403
[19] Kambali I, Suryanto H 2016 *Journal of Engineering and Technological Sciences* 48 482
[20] Gladys M J, Kambali I, Karolewski MA, Soon A, Stampfl C, O’Connor DJ 2010 *J. Chem. Phys.* 132 024714
[21] Kambali I, O’Connor DJ, Gladys MJ, Karolewski MA 2008 *Appl. Surf. Sci.* 254 4245
[22] Ziegler JF, Ziegler MD, Biersack JP 2010 *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 268 1818
[23] Koning A, Rochman D 2012 *Nuclear Data Sheets* 113 2841
[24] Kambali I 2017 *Makara J. Science* 21 125
[25] Kambali I 2014 *Atom Indonesia* 40 129
[26] Kambali I, Saptiama I, Suryanto H 2017 *Aceh International Journal of Science and Technology* 6 104
[27] Kambali I, Suryanto H, Parwanto 2016 *Atom Indonesia* 42 1
[28] Kleeven W, Abs M, Delvaux JL, Forton E, Jongen Y, Romao LM, Nactergal B, Nuttens V, Servais T, Vanderlinden T, Zaremba S 2011 *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 269 2857