Prediction of ^{211}At production using the Monte Carlo code MCNPX

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1. Introduction

Targeted α-particle radiation therapy is considered to be a promising treatment option for eradicating disseminated tumor cells and small clusters of metastases such as micrometastatic lesions, residual tumors margins remained after debulking the primary tumor by surgery [1, 2]. Among the α-particle emitting radionuclides, ^{211}At is the most promising radionuclide for targeted cancer therapy due to its decay properties. ^{211}At has a half-life of 7.214 h, which is sufficient for its production, labeling, dispensing, transportation, quality control and administering the radiolabeled compound. The range of α-particles produced by the decay of ^{211}At are less than 70 μm in water and soft animal tissues with a LET between 100 and 130 keV/μm, which is about the maximum RBE for heavy ions [3]. The survey carried out by Barbet *et al* revealed that the most favorable radionuclides for therapeutic applications were ^{211}At and ^{67}Cu [4].

Although it is possible to produce ^{211}At via various methods such as ^{209}Bi(^{7}Li,5n)^{211}Rn→^{211}At, ^{209}Bi(^{3}He,n)^{211}At, ^{nat}U(p,x)^{211}At and ^{234}Th(p,x)^{211}Rn→^{211}At), these methods are not useful for meeting the demands of routine production because they are not efficient, requiring particle energies between 160 and 660 MeV and extensive separation procedures. The most preferred production route for ^{211}At production is via cyclotron bombardment of natural bismuth targets with about 29 MeV α-particles [5].

In this study, the production method is based on the nuclear reactions ^{209}Bi(α,2n)^{211}At, which has a threshold around 21 MeV and reaches the maximum cross section of about 900 mb at 30 MeV. However, one cannot take advantage of the full range of the beam energies suitable for production of ^{211}At because of concerns about generating ^{210}At with half-life of 8.3 h. This radionuclide is problematic because its decay leads to the production of daughter ^{210}Po, which is an α-particle (5.304 MeV) emitting radionuclide with a physical half-life of 138.4 d and a biological half-lives ranging from 30 to 50 d, unnecessarily giving rise to bone marrow toxicity [6].

Our goal has been to model fluxes from a ^{209}Bi target and to subsequently calculate the yields of α-emitter ^{211}At and ^{210}At using 45 MeV α-beam.

2. Methods and Results

Targets consisted of 1.0 mm ^{209}Bi and Al degrader. To calculate the thickness of Al degrader for maximizing the yield of ^{211}At while keeping the content of ^{210}At at an acceptable level, the α-beam energy distribution was simulated after the different thickness of aluminum degraders using the MCNPX. The average α-beam energy was also compared with the results calculated using the Eloss and SRIM code. MCNPX is a general-purpose Monte Carlo radiation transport code for modeling the interaction of radiation with matter. In particular, this code can be used to simulate the irradiation of target materials with hadrons to optimize target design and study the activation of the materials. We use it to simulate alpha particle irradiations, to model particle fluence, energy distribution.

The results of the simulations were reported by MCNPX in terms of α-particle flux (α-particle fluence per cm^{2} per source particle simulated) in the ^{209}Bi target. To estimate radionuclide activity at the EOB(end of bombardment), the particle distribution function *P(E)* was reported from the F4 tally output (fluence) data that were normalized over the entire particle energy range.

The energy distribution function for α-particles was further utilized to calculate radionuclide yield estimates for the formation of ^{209}Bi(α, 2n)^{211}At and ^{209}Bi(α, 3n)^{210}At. The energy distribution function and the cross section *σ(E)* can be used to calculate the product function *P(E)σ(E)*. Energy-dependent cross section *σ(E)* data was used from literature experimental cross sections as shown in Fig. 1 [7].

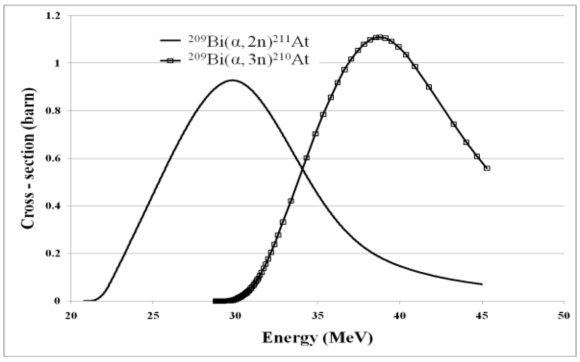

Fig. 1. Excitation functions for the α-particle-induced ^{209}Bi(α,2n)^{211}At and ^{209}Bi(α,3n)^{210}At reactions on natural bismuth target.

Integrating and solving the following differential equation for an instable product nuclide result can determine the identities of the generated radionuclides:

$$A(t) = \int_0^{E_{\max}} P(E)\sigma(E)dE\frac{dN_\alpha}{dt}N\left(1 - e^{-\lambda t}\right)$$

where *A(t)* is the radionuclide radioactivity, dN_α/dt is the intensity of the irradiating α-particles(number of α-particles/cm^{2}s), λ is the radionuclide decay constant and t is the duration of irradiation.

The transmitted α-beam energy spectra for the Al degraders of various thicknesses are shown in Fig. 2. The thicknesses of the Al degraders were varied in the ranges of 0.30 ~ 0.42 mm. The average value, $E_{\alpha,\text{av}}$, was evaluated and the energy straggling in the α-beam energy was determined from the spectra as the FWHM by using Gaussian fitting as shown in Table 1. The all energies, $E_{\alpha,\text{av}}$, calculated with MCNPX are in good agreement with those calculated using the SRIM and Eloss. The $E_{\alpha,\text{av}}$ decreased and the energy straggling increased with increasing the thickness of Al degrader. Degrading in Al leads to broader energy distribution and FWHMs were ranged from 0.424 to 0.543 MeV.

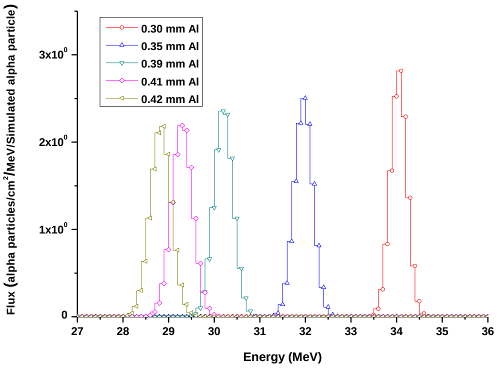

Fig. 2. Energy distributions of the 45 MeV α-particles on the bismuth target entrance after the different thickness of aluminum degraders.

Table 1. Calculated average energy, $E_{\alpha,\text{av}}$ (MeV), after the different thicknesses of aluminum degraders and FWHM (MeV) of α-beam energy distributions calculated using MCNPX.

Aluminum degrader thickness	Calculated average energy (MeV)		
	Eloss	SRIM	MCNPX (FWHM)
0.30 mm	33.940	33.964	33.956 (0.424)
0.35 mm	31.818	31.849	31.809 (0.478)
0.39 mm	30.052	30.076	30.069 (0.497)
0.41 mm	29.132	29.159	29.170 (0.540)
0.42 mm	28.663E	28.691	28.706 (0.543)

In Fig. 3, data from previously published studies and present study on ^{211}At production is presented. In general, the yield of ^{211}At per μAh calculated in this study is similar to the older data. Differences in the irradiation times, the effective target diameter, vaporization of ^{211}At from the target and discrepancies in the determination of the alpha beam and the energy distribution could also possibly contribute to the difference in yield observed in our study compared with the older data.

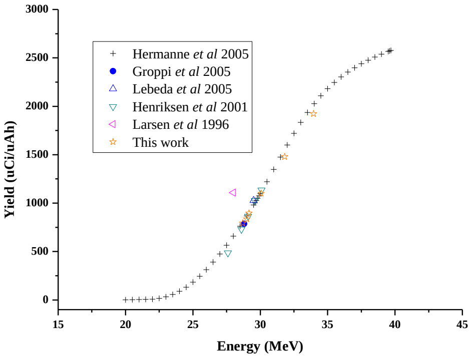

Fig. 3. Previous and current studies on the production of ^{211}At

3. Conclusions

We demonstrated that MCNPX provide a useful tool for the simulation of α-beam irradiations for the purpose of radionuclide production. ^{211}At and ^{210}At production yield estimates were obtained using modeled α-beam energy distribution in the target and cross section. Estimates largely agree with data from previously published studies.

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