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FLUKA SIMULATIONS OF ^{225}Ac PRODUCTION USING ELECTRON ACCELERATORS: VALIDATION THROUGH COMPARISON WITH PUBLISHED EXPERIMENTS

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Abstract

Targeted Alpha Therapy (TAT) is an active area of study worldwide. This technique has shown a potential in nuclear medicine to treat metastatic disease by alpha particles that deposit energy in small regions nearby cancer cells. ^{225}Ac is an important alpha-emitting that can be used for cancer TAT. This radioisotope shows good potential for medical applications, therefore it is important to study ways of increase its production and availability. One possible path for the ^{225}Ac production is to irradiate a radium target (^{226}Ra) on a linear electron accelerator (LINAC). Isotope production studies could be implemented using computational tools. In this work, Monte Carlo simulations with FLUKA code were performed and compared to experimental results. We studied ^{225}Ac production by photonuclear reactions using a 24 MeV electron beam LINAC hitting a tungsten electron-photon converter. Different energies and geometries were also simulated to obtain optimal production conditions. The specific activity values obtained with simulations had a good agreement with published experimental results.

INTRODUCTION

^{225}Ac Production

The use of new radioactive isotopes, in particular actinium-225, for the diagnosis and therapy of various diseases is one of the major fronts of nuclear medicine. The ^{225}Ac is a parental radioisotope for the preparation of ^{213}Bi, an isotope also used in nuclear medicine. The ^{225}Ac has a half-life of approximately 10 days, and the daughter isotopes are short-lived emitters (see Fig. 1).

The nuclear properties of ^{225}Ac allow its application for the same purposes, specifically for targeted alpha therapy (TAT). This technique has been developed in several countries, highlighting the recent realization by the Brazilian Nuclear and Energy Research Institute IPEN/CNEN of the first labeling of the glycoprotein PSMA with actinium-225, to use in the treatment of metastatic prostate cancer.

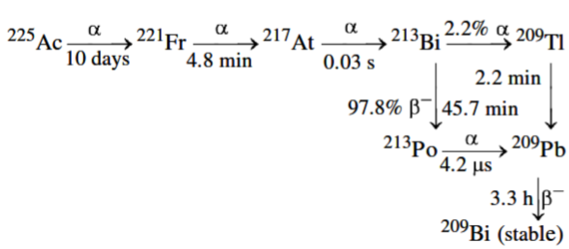

Figure 1: Decay scheme of Actinium 225.

To produce ^{225}Ac, it is common to use an electron accelerator, which may be a cyclotron, betatron, or a linear accelerator (LINAC). We irradiate electrons with energies of a few dozen MeV in a converter, which has the function of converting the electron beam into photons by interaction of them with matter. The converter is a simple layer of material, usually a few millimeters of tungsten, where electrons interact, generating bremsstrahlung radiation (see Fig. 2). These photons then hit a target containing a specific material, generating a parent isotope of the one we want to produce.

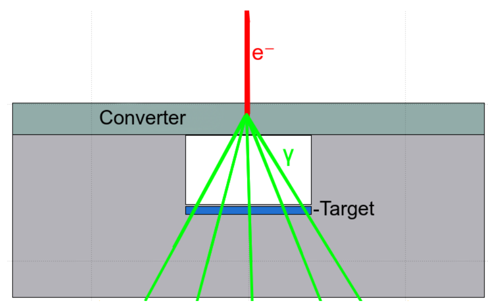

Figure 2: Representation of an electron beam hitting a converter and generating bremsstrahlung photons into a target.

When radiating ^{226}Ra, it is produced ^{225}Ra by (γ, n) reaction, which needs some time after the irradiation to decay to ^{225}Ac until it reaches its maximum activity, called cooling time. For the ^{225}Ra producing ^{225}Ac, it happens in approximately 17.5 days (see Fig. 3).

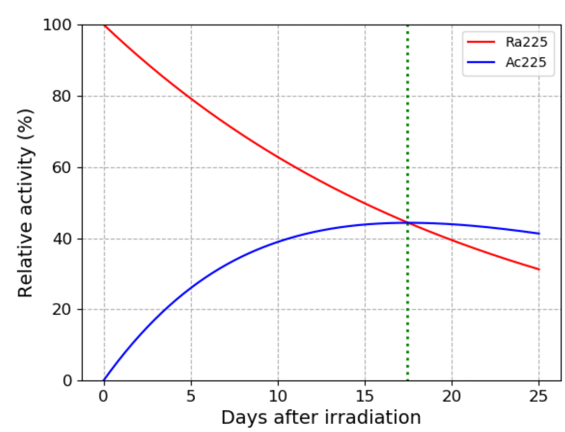

Figure 3: Relative activity of ^{225}Ac and ^{225}Ra in function of cooling time in days.

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Monte Carlo Code Fluka

The Monte Carlo Method (MCM) is based on repeated random sampling to obtain numerical results. With the use of randomness to solve problems that might be deterministic, in principle, is possible to approach non-stochastic results based on probability distribution that describes the problems.

Since the MCM implementation in 1946 by the mathematicians Stanislaw Ulam and John von Neumann, many algorithms was developed, including the Monte Carlo code FLUKA [1], as well as the graphic interface FLAIR [2], created by CERN and INFN for simulating the transport of particles and its interaction with matter.

With FLUKA is possible to simulate an experiment setting a geometry, materials, particle's properties, irradiation and detector's parameters, resulting in values of exposure, spectra, as well as production and activity of radioisotopes.

MATERIALS AND METHODS

Comparison of Experimental Measurements and FLUKA Results

At first, it was necessary to evaluate the effectiveness of the Monte Carlo Code FLUKA for production of radioisotopes, specifically for the reaction ^{226}Ra (γ, n) and the ^{225}Ra decay. For this, a geometry was implemented in computational simulations based on experiments developed by Maslov, Sabel'nikov and Dmitriev [3,4].

That consists of an electron beam with energy of 24 MeV and diameter of 5 mm reaching a 2 mm thick tungsten converter.

A sample of ^{226}Ra was placed in the bottom of a cylindrical cavity of an aluminum support with a 8 mm diameter and 5 mm depth, hermetically sealed with a 0.1 mm thick aluminum, directly in front of the converter (see Fig. 4). Then, the converter was irradiated for 20 hours with an electron current of 15 μA and underwent a cooling time of 18 days for the activity of ^{225}Ac to reach its maximum.

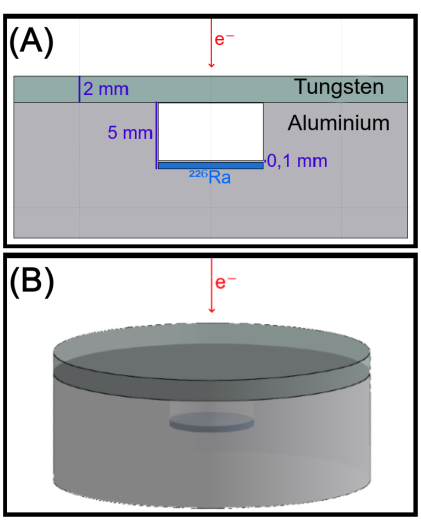

Figure 4: Geometry for simulating irradiation of ^{226}Ra [4] in (A) sagittal cut and (B) a 3D projection.

Since it is a nuclear reaction and the Maslov's results are given as specific activity, that means it's normalized by the mass of ^{226}Ra, as well by the beam current and hours of irradiation. To rise the probability of photon interaction with the target, it was considered a higher amount of mass of pure ^{226}Ra, for equivalent but more accurate results in a shorter period of time.

Improvement in the Production of ^{225}Ac

Confirming the correct response of FLUKA code for the reactions of interest, it was developed tests with the parameters of the experiment, in order to improve the ^{225}Ac production within the experimental reality that we have. This includes taking into account the amount of material used, tangible beam energies and the dose absorbed by the components.

Parameters, as the energy of the primary beam and the geometry is easily manipulated in the FLUKA code settings. Then, to improve the ^{225}Ac production, we simulate different scenarios and compare the results.

In this scenario, greater energies for the primary beam should lead to greater specific activities. Once that to happen the ^{226}Ra(γ, n)^{225}Ra reaction, the minimum energy of the photon need to be 6.4 MeV [5], and greater primary electron beam's energies lead to a greater fluence of more energetic photons. But this increase in energy lead to a rise in the absorbed dose by the components. Then, there is a compromise between the production of ^{225}Ac and the heat increase in components.

FLUKA Code Parameters

In order to carry out the simulations proposed in this study, since FLUKA transport particles in a very broad range of energy, its import to set the correct parameters to enable the interactions of interest.

Using the MATERIAL card, the material of ^{226}Ra with a density of 5.5 g/cm^3 was set. To enable interaction with its neutrons and their transport, the cards LOW-MAT and LOW-NEUT were used.

The irradiation time was configured with the IRRPROFI card, configuring an irradiation with 20 hours and 15 μA.

An activity detector was used, defined by the RESNUCLEi card together with an auxiliary DCYSCORE card. The decay times were configured with the DCYTIMES card, these being just after irradiation to 25 days after.

In addition, dose detectors were used in the converter, in the ^{226}Ra target and in the aluminum support with the USRBIN card. These used to evaluate the dose that each component is subject to.

RESULTS AND DISCUSSION

Comparison of Experimental Measurements and FLUKA Results

The activities of all radionuclides produced was evaluated. A large part of these radionuclides have a relatively short

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half-life, making ^{225}Ac and its daughters radionuclides the majority after 18 days of decay (see Table 1).

Table 1: Main Radionuclides Generated, in Relation to the Activity, 18 days After Irradiation of ^{226}Ra Target

Radionuclide produced	Activity (Bq/µA/h/mg ^{226}Ra)
^{225}Ac	507.6
^{225}Ra	448.6
^{221}Fr	507.6
^{217}At	507.1
^{213}Po	497.2
^{213}Bi	507.2
^{209}Pb	508.5

The activity of ^{225}Ac reached after 18 days was 507(20) Bq/µA/h/mg, which agrees with the Maslov's experimental results of 550 Bq/µA/h/mg, differing only by 7.8%.

Improvement in the Production of ^{225}Ac

To optimize the ^{225}Ac production, the beam energy was varied between 24 MeV to 90 MeV (see Fig. 5).

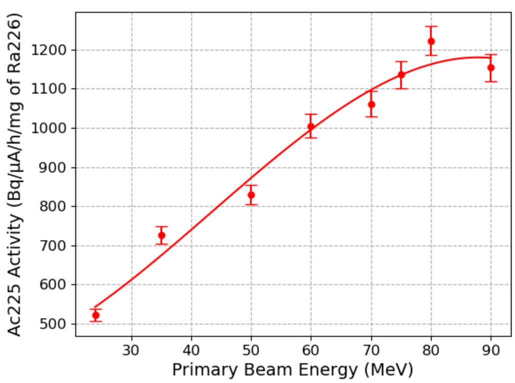

Figure 5: ^{225}Ac activity in function of electron energy beam.

The activity has a plateau close to 80 MeV. Therefore, rise the energy up this value doesn't affect significantly the activity of ^{225}Ac produced.

Comparing the dose absorbed by the components with different electron beam energies, it's possible to shape the experiment for scenarios that we can deal with, in terms of the increase in heat by the components due to irradiation.

It was established that in the scenario proposed by Maslov the temperature increase in the components was not higher than 100 °C [4]. Assuming that value as the maximum heat for the beam energy used in Maslov's experiments for all components and the linearity between the absorbed dose in component obtained with FLUKA and the heat increase in it, the maximum heat for tungsten converter, aluminium support and radium target was calculated (see Table 2).

The heat increase in the aluminium support and the tungsten converter didn't have a significant variation with the beam energy. On the other hand, the ^{226}Ra target had a linear absorbed dose with the ^{225}Ac activity produced.

Table 2: Maximum Heat Increase in Each Component of the Experiment

Energy (MeV)	Converter (°C)	Support (°C)	Target (°C)	Activity (Bq/µA/h/mg)
24	100.00	100.00	100.00	507.6
35	92.07	107.88	139.12	726.3
50	88.33	108.12	180.02	832.2
60	87.62	108.39	198.02	1005.6
70	87.43	109.20	211.38	1061.5
75	87.46	109.68	216.84	1136.0
80	87.49	110.26	221.58	1222.8
90	87.67	111.43	229.71	1154.6

CONCLUSION

In this study, previously published experimental setup adopted by Maslov, Sabel'nikov and Dmitriev [3,4] for ^{225}Ac production was simulated in Monte Carlo code FLUKA and the results differ only by 7.8%, showing a good agreement between both methodologies.

Beyond this, it was analysed the variation in activity of ^{225}Ac changing the energy of electron beam, which it was noticed that there is a plateau of the activity produced in around 80 MeV. The increase in energy impact on the heat in components, an important parameter for experiment definitions. The heat in the ^{226}Ra target is the most important, it increases linearity with the ^{225}Ac production and it should be limited by the efficiency of the cooling system. This demonstrates a compromise between the activity produced by the isotope of interest and the heat delivered in the components.

Therefore, FLUKA demonstrated to be a powerful tool to study different setups for the irradiation parameters, being fundamental to predict and optimize the production of ^{225}Ac and many others radioisotopes of interest.

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