Laser-driven radioisotopes production at SCAPA for medical and industrial application

G Battaglia[1], E Brunetti[1], M M R Chishti[2], G Lorusso[3], D O'Donnell[2], M Scheck[2], S M Wiggins[1] and D A Jaroszynski[1]

[1] Department of Physics, University of Strathclyde, G4 0NG
[2] School of Engineering and Computing, University of the West of Scotland, Paisley PA1 2BE
[3] National Physical Laboratory, Teddington TW11 0LW

E-mail: `d.a.jaroszynski@strath.ac.uk`

Abstract. Isotopes for nuclear medicine are scarce and expensive. Researchers worldwide are exploring new production methods to avoid the dependence on nuclear reactors as sources to satisfy future isotope demands. Photo-nuclear reactions have hitherto been used as a tool for studying the nuclear structure. Laser wakefield accelerators (LWFAs) are very compact accelerators capable of producing high energy electron beams. In this paper we investigate the possibility of using LWFAs to produce ^{225}Ac via photo-spallation reactions.

1. Introduction

Radioisotopes are commonly used both for diagnostics and therapy in medicine. Positron emitters (e.g. ^{18}F) are usually used for positron emission tomography and gamma emitters (e.g. ^{99m}Tc) are used for single photon emission computed tomography while alpha emitters (e.g. ^{223}Ra) and beta minus emitters (e.g. ^{90}Y) are used for targeted radiation therapy (TRT) [1]. Over 140 radioisotopes are used daily for medical procedures worldwide, but 90% of these utilise only 10 radioisotopes [2]. Moreover, the supply chain is quite fragile. The majority of the nuclear reactors used for isotopes production are several decades old and and several face imminent closure [3]. During 2008 there was a reduction of planned medical services of up 70% due to the temporary shut down of some of the reactors producing ^{99}Mo, parent isotope of ^{99m}Tc [3]. This is a compelling reason why researchers are looking for new techniques to produce radioisotopes. In this paper we present Montecarlo simulations that explore the feasibility of using high-energy photo-spallation reactions triggered by photons from laser wakefield accelerators (LWFAs), as an option for producing future radioisotopes.

1.1. Photo-spallation reactions

Photo-nuclear reactions are triggered by photons, which have an advantage over hadrons in that they avoid major modifications to the structure of the nucleus arising from the interaction [4]. Spallation reactions occur when the energy of the projectile or photon is sufficiently high for it to interact with single nucleons inside the nucleus [5]. This results in ejection of several nucleons (evaporation) or fission of the nucleus. The majority of studies of photo-nuclear reactions have hitherto been focused on nuclear photo-fission, and in particular on whether the photo-fission cross section σ_f could exhaust the photo-absorption cross section σ_{abs} for photon energies above

50 MeV [4][6][7]. A series of measurements from JLab and other facilities have shown that for energies from hundreds of MeV up to few GeV $\sigma_f \not\equiv \sigma_{abs}$ and other channels (evaporation) have to be taken into account in calculating the photo absorption cross section [6][7]. In particular, for ^{232}Th the photo-fission channel only contributes to 55-70% of the total σ_{abs} cross section in the hundreds of MeV-GeV region [4]. The aim of this study is to characterize the spectrum of the products of the remaining 45-30% to investigate if any isotopes relevant for nuclear medicine (^{225}Ac specifically) is produced in significant quantities.

1.2. Laser WakeField Accelerator

LWFAs are very compact electrons accelerators that utilise electrostatic fields arising from charge separation in plasma arising from the interaction of high-intensity ($> 10^{18}$ W/cm^2 for $\lambda \approx 1$ μm) laser pulses with plasma [8]. This is a highly nonlinear process, in which the ponderomotive force of the laser electromagnetic field creates a few micron size "bubble" of positive ions surrounded by a thin sheath of electrons. The bubble contains fields with gradients that can exceed 100's GV/m, which is much higher than possible with conventional accelerators [9]. The high gradient makes it is possible to accelerate electrons up to several GeV energies over a distance of a few centimetres, but at relatively low repetition rate. Progress is being made to extend the repetition rates of LWFAs beyond 10 Hz [10].

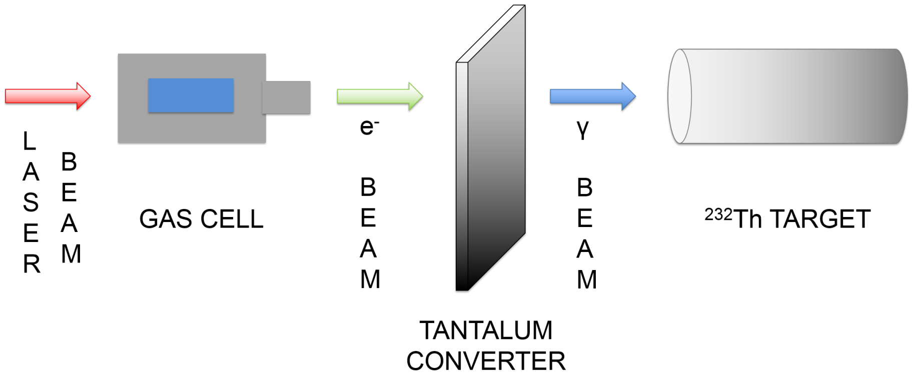

Figure 1. Outline of the setup used in the simulations. The electron beam has a bunch charge of 50 pC with a repetition rate of 1 Hz and a 2 mrad divergence, the Tantalum converter is 16 mm thick, the ^{232}Th target is 1.5 g .

2. FLUKA simulations

Simulations have been performed using FLUKA, a general purpose montecarlo code that can simulate the transport of more than 60 different types of particles over a wide range of energies (up to the TeV range) using up-to-date physical models with minimal free parameters improving the predictability of the results when no experimental data are available [11]. The parameters used in the simulations presented here are modelled on the performance of a LWFA driven by the 350 TW laser system of the Scottish Centre for the Application of Plasma-based Accelerators (SCAPA) [12]. The experimental setup that has been simulated is shown in Fig. 1. The aim of the study is to explore the feasibility of using high energy photon beams (hundreds of MeV) for the production of isotopes. To produce such high energy gammas via bremsstrahlung a high energy electron beam is required. Therefore simulations assume an electron beam with an average energy of 700 MeV, a relative energy spread of 10%, an average current of 50 pA (50 pC bunch charge at 1 Hz repetition rate) and an irradiation time of 10 hours. The target consists of

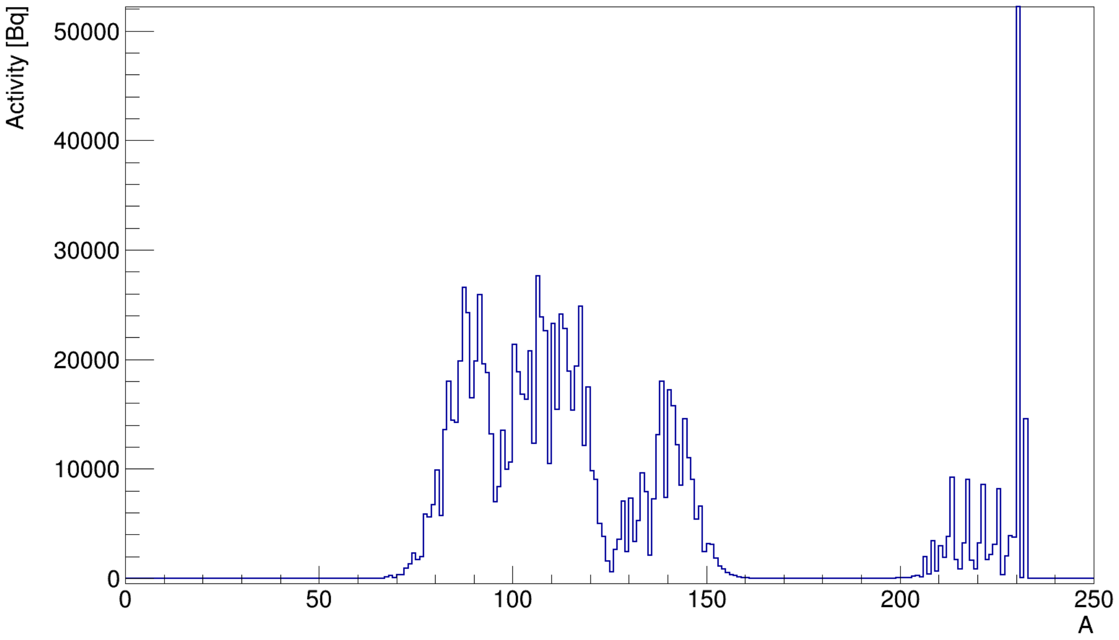

Figure 2. The results of the FLUKA simulations. The X axis is the nuclear mass number A, the Y axis is the activity in Bq. Peaks on the leftside of the graph represents the fission products, while the group of peaks on the right side represent the evaporation products.

1.5 g of ^{232}Th. The results of the simulations are shown in Fig. 2. The produced activity of ^{225}Ac after 10 hours of irradiation is 33 ± 1 Bq according to the results of FLUKA. Although FLUKA takes into account all the possible reactions, including decay from isotope above Actinium in the decay chain, those activities are 10^{-6} Bq of ^{233}U, 10^{-1} Bq of ^{229}Th and less than 2 Bq of ^{225}Ra. This means that the majority of the ^{225}Ac is a results of the photo-spallation reaction, while their contribution from the decay channel is minimal. The activity of each isotope in Fig. 2 is much lower of that required for a preclinical or clinical nuclear medicine use, where hundreds of MBq or GBq are required [13]. However the relation between the reaction rate R and the photon flux ϕ is linear, as given by the formula $R = N \cdot \phi \cdot \sigma$, where N is the number of atoms in the target and σ is the reaction cross section [14]. Therefore it is plausible that future LWFA with higher charge of 100's pC [15] and repetition rate of 10's of kHz [16] will be able to produce the useful levels of activity.

3. Conclusion

Photo-spallation reactions are a very powerful tool for the study of nuclear structure, which so far has not been explored for practical application. The high photon energy required limits the number of accelerators and radiation sources capable of triggering them. LWFAs are very compact machines capable of accelerating electron beams to very high energy over very short distances. The Montecarlo simulations presented in this paper provide an estimate of the yield of ^{225}Ac produced from a ^{232}Th target via photo-spallation reactions triggered by bremsstrahlung photons generated with a laser wakefiled accelerator. An experiment to confirm these results will be carried out at SCAPA facility in the near future.

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