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Activation of accelerator construction materials by heavy ions

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ABSTRACT

Activation data for an aluminum target irradiated by 200 MeV/u ^{238}U ion beam are presented in the paper. The target was irradiated in the stacked-foil geometry and analyzed using gamma-ray spectroscopy. The purpose of the experiment was to study the role of primary particles, projectile fragments, and target fragments in the activation process using the depth profiling of residual activity. The study brought information on which particles contribute dominantly to the target activation. The experimental data were compared with the Monte Carlo simulations by the FLUKA 2011.2c.0 code. This study is a part of a research program devoted to activation of accelerator construction materials by high-energy ($\geqslant$200 MeV/u) heavy ions at GSI Darmstadt. The experimental data are needed to validate the computer codes used for simulation of interaction of swift heavy ions with matter.

1. Introduction

Accelerators and their components may get activated due to beam losses during machine operation. Activation becomes an important issue especially for high-power hadron facilities. Activation studies of accelerator construction materials started in 2007 in the framework of preparation of the FAIR project (Facility for Antiproton and Ion Research) [1–5]. Copper, aluminum, and stainless steel targets were irradiated by different heavy-ion beams at different energies. The aim of these experimental studies was to identify the nuclides induced in the most common accelerator construction materials, to measure their residual activity (relevant for the hands-on maintenance and radiation protection issues) and to determine the depth profiles of the residual activity. The latter is relevant for validation of the physical models and data libraries implemented in the corresponding simulation codes like FLUKA and SHIELD [6]. In this paper, the latest results for aluminum target, 200 MeV/u ^{238}U beam and the FLUKA 2011.2c.0 code [7] are presented.

2. Experiment and methods

The aluminum target was irradiated in the stacked-foil geometry with 200 MeV/u ^{238}U beam. There were altogether 70 target foils used for depth-profiling of the residual activity. In order to achieve reasonable depth resolution, the target foils were 0.1 mm thick. The aluminum foils had diameter 10 cm, purity 99.9% and density 2.7 g/cm^3 at 20 °C. The 200 MeV/u ^{238}U^{73+} beam was delivered by the SIS-18 heavy-ion synchrotron at GSI Darmstadt [8]. The target was irradiated in the air. The beam-line was terminated by a vacuum window made of stainless steel, 100 μm thick. The air–gap between the vacuum window and the target was 61 cm. In total, 2.8×10^{12} ions were delivered to the target.

The target foils were analyzed by gamma-ray spectroscopy. The gamma-ray spectra were measured either individually or in groups of 5 foils in a low-background container by a high-purity germanium (HPGe) detector. Two series of measurements were performed: (a) 6–20 days, and (b) 130–180 days after the end of irradiation. The experimental data were compared with the Monte Carlo simulations by the FLUKA 2011.2c.0 code [7]. The measured residual activities were extrapolated backwards in time to the end of irradiation and normalized per one incident ion.

3. Results and discussion

The nuclides induced in the target can be classified into two groups: (a) target-nuclei fragments and (b) projectile fragments. The different characteristic shape of depth-profile of these two groups is clearly distinguishable. The target-nuclei fragments are present starting from the 1st target foil and extend even well beyond the range of the primary projectiles. The latter indicates that the target activation is caused not only directly by the primary projectiles, but also by lighter secondary particles that have range

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longer than the range of the primary particles (because of lower proton number, Z). In contrary, the presence of the projectile fragments in the foils upstream the projectile range is improbable (a small amount of them can be present for example due to the backscattering events inside the target). Their depth-profiles start at the range of the primary ions, which corresponds to the situation when the projectile gets fragmented at the very end of its track in the target. In opposite to that, if it gets fragmented at the very beginning of its track, the resulting lower-Z fragments have longer ranges, and stop beyond the range of the primary projectiles. As an example, depth-profiles of the residual activity of ^{7}Be, ^{22}Na, ^{88}Y, ^{113}Sn, ^{127}Xe, ^{146}Eu, ^{206}Bi, and ^{237}U are presented to illustrate the characteristic depth-profile shape of the target-nuclei fragments and the projectile fragments.

Penetration of the ^{238}U ions (primary projectiles) in the target calculated by FLUKA has been cross-checked with the experiment using the ^{237}U tracking [9] (see Table 1). The FLUKA code predicted the presence of the ^{237}U in two foils only (Nr. 34 and Nr. 35), but we identified it in the foil Nr. 36 as well. The range and range straggling of the ^{237}U ions calculated by FLUKA is 3.423 mm ± 0.007 mm, whereas the range determined experimentally is 3.456 mm ± 0.004 mm. FLUKA also predicts about 40% lower production of ^{237}U.

The measured and simulated depth-profiles of the residual activity of ^{7}Be, ^{22}Na, ^{88}Y, ^{113}Sn, ^{127}Xe, ^{146}Eu and ^{206}Bi are presented in Figs. 1–7. Experimental data from the 1st and the 2nd set of measurements are labelled as “Measurement (1st)” and “Measurement (2nd)”, respectively.

The depth-profiles of ^{7}Be and ^{22}Na are typical examples of the target-nuclei fragments (see Figs. 1 and 2, respectively). The simulation is in agreement with the 1st and the 2nd set of measurements only in the first foils of the target. In the depth of about 1.25 mm (the vertical line 150 MeV/u), discrepancies between the simulation and the experimental data become evident. There are also disparities between the 1st and the 2nd set of measurements in the range region. The activities of ^{7}Be and ^{22}Na were affected by short-lived nuclides in the case of the measurements shortly after the end of irradiation. Several data points had to be excluded from the measured depth-profiles of the ^{7}Be and ^{22}Na for that reason. Generally, FLUKA overestimates the residual activity of these nuclides. We observed discrepancies in the production of these nuclides between the simulation and the experiment below the projectile energy of about 150 MeV/u. In case of ^{7}Be, the largest difference is in the depth corresponding to the projectile energy of 125 MeV/u (see Fig. 1). That is the energy, at which the change between the two nucleus-nucleus interaction models in FLUKA takes place. More specifically, the Relativistic Quantum Molecular Dynamics Model (used for higher energies) is replaced by the Boltzmann Master Equation (used for lower energies).

The depth-profiles of the residual activity for projectile fragments (^{88}Y, ^{113}Sn, ^{127}Xe, ^{146}Eu and ^{206}Bi) are shown in Figs. 3–7. In this case, the simulated and experimental data are in a good agreement. The difference between calculated and measured residual activities in the range region is from 3% up to 25%.

Table 1
Activity of ^{237}U in Al target induced by 200 MeV/u ^{238}U beam. The depth corresponds to the middle of the foil.

Foil Nr.	Depth (mm)	Activity of ^{237}U (Bq/mm/ion)	
		Simulation	Experiment
34	3.35	$1.262 \times 10^{-8} \pm 1 \times 10^{-10}$	$1.546 \times 10^{-9} \pm 2 \times 10^{-11}$
35	3.45	$2.710 \times 10^{-8} \pm 1 \times 10^{-10}$	$6.276 \times 10^{-8} \pm 7 \times 10^{-11}$
36	3.55	0	$3.461 \times 10^{-9} \pm 2 \times 10^{-11}$
Total		$3.973 \times 10^{-8} \pm 2 \times 10^{-10}$	$6.776 \times 10^{-8} \pm 8 \times 10^{-11}$

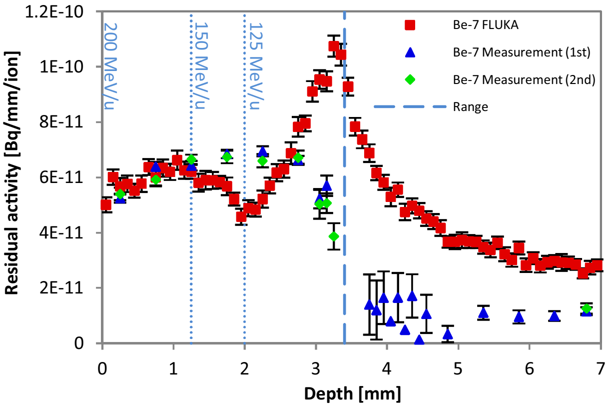

Fig. 1. Depth-profiles (measured and simulated) of the residual activity of ^{7}Be induced in Al target by 200 MeV/u ^{238}U beam.

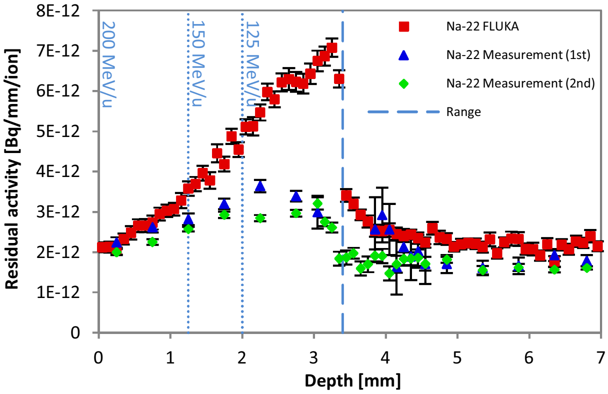

Fig. 2. Depth-profiles (measured and simulated) of the residual activity of ^{22}Na induced in Al target by 200 MeV/u ^{238}U beam.

Table 2
The longest possible range of the projectile fragments and the target-nuclei fragments calculated by FLUKA 2011.2c.0 code.

	Range ± range straggling (mm)
^{7}Be	53.545 ± 0.224
^{22}Na	21.840 ± 0.053
^{88}Y	6.820 ± 0.008
^{113}Sn	5.370 ± 0.007
^{127}Xe	5.178 ± 0.007
^{146}Eu	4.383 ± 0.005
^{206}Bi	3.622 ± 0.004

The depth-profiles shown in this paper have been selected to cover some characteristic cases. The basic difference in the shape of the depth-profiles between the target-nuclei activation and projectile fragmentation has already been discussed. However, more information about the physics of the activation process can be gained by the depth-profiling of the residual activity. In case of the target-nuclei activation, the contributions from the primary particles and secondary particles can be distinguished by comparing the residual activities in front of and behind the range of the primary particles. The activation behind the range must be free from the contribution from the primary projectiles, whereas the activation in front of the range consists of both, the primary particles as well as the secondary ones. The contribution from the primary particles can be determined by subtracting the activity just behind the range from the activity in the range region. In case of