

ACTIVATION OF ALUMINIUM BY URANIUM*

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Abstract

The research into the activation of materials used for accelerator components is performed at GSI as a part of studies selecting appropriate materials for FAIR. The project "Verification of Monte Carlo transport codes: FLUKA, MARS and SHIELD" was started in the frame of these studies. Series of irradiations were completed already. This paper presents the results of irradiation of aluminium targets with uranium. Experimentally achieved depth profiles of nuclides' production rates and the stopping range of primary ions are compared with simulations. Correspondences and discrepancies of the experiment with the simulations are discussed.

INTRODUCTION

During the operation of accelerating facilities, their components are activated because of beam losses, which could lead to unnecessary personnel exposure. Thus the estimation of the activity levels is needed to design proper shielding and decide whether the access to the experimental area is possible.

The FLUKA simulation package [1, 2] is widely used for the estimation of radiation hazards. The physical models implied in the code are constantly being further developed. Therefore verification is needed to make sure that the simulations give reasonable results.

Activation studies of accelerator materials were started at GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt within the preparation for the high-current heavy-ion Facility for Antiproton and Ion Research (FAIR). Several irradiation experiments on selected materials and under different irradiation conditions were completed [3-5].

Here we present the results of the uranium irradiation of aluminium targets. The aluminium was chosen because it represents a material with relatively low atomic number ($Z = 13$) that is expected to get less activated than high- Z materials studied in previous experiments. The aluminium components should be preferred in accelerator areas with high beam losses (e.g. extraction region, beam-diagnostics components, etc.).

The goal of the study was to measure the stopping range of uranium at different energies, to study the dependences of nuclides' production rates on depth and to compare the experimental results with simulations.

EXPERIMENT AND METHODS

Two types of targets were irradiated. The truncated cylinder covered with organic material (Fig. 1) was used to measure the stopping range. The experimental technique is based on the idea that ions leave the trace on the organic material, the position of maximum blackening corresponds to the maximum of energy deposition.

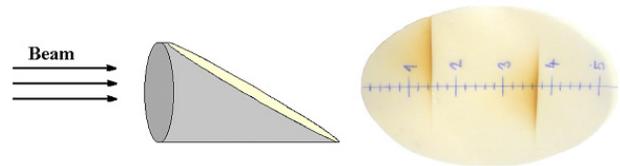


Figure 1: Truncated cylinder covered with organic material.

The cylinders assembled from discs (Fig. 2) were irradiated for depth profiling of the nuclides' production rates. The stack contained activation foils and spacers. The activation foils were used to get individual data-points for depth profiling, by measuring the γ -spectra of residual activity. The spacers were used to define the depth-points of the profiles by keeping the distance between the activation foils.

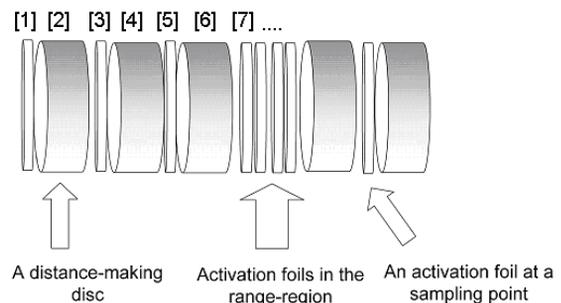


Figure 2: Scheme of the target for depth profiling of residual activity.

The irradiations were done at two energies of the primary ions: 500 MeV/u and 950 MeV/u. The truncated cylinder was irradiated two times by ions of both energies until the total number of projectiles on the target reached $\sim 2.5 \cdot 10^{11}$ ions for each energy. Two different cylindrical targets were irradiated for depth profiling of residual activity. The parameters of these irradiations are presented in Table 1.

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Table 1: The Parameters of the Irradiations

Energy of the beam, MeV/u	Number of projectiles	Target thickness, cm
500	$5.07 \cdot 10^{11}$	2.77
950	$1.02 \cdot 10^{12}$	7.20

Gamma-spectra were measured by high-purity germanium (HPGe) detector after the end of the irradiation. The activation foils were measured 3 times at different time points (6 hours – 3 months after the end of the irradiation).

SIMULATIONS

The stopping range of the uranium ions was found by simulating the experiment with FLUKA (2008.3b) [1, 2] and ATIMA 1.2 [6]. The results are shown in Table 2, energy losses in 100 μm stainless steel vacuum window and 1m air gap are taken into account.

Table 2: Stopping Ranges of Uranium Ions

Energy of the beam, MeV/u	Monte Carlo Code	Stopping range±straggling, mm
500	ATIMA	15.31 ± 0.01
	FLUKA	15.80 ± 0.02
950	ATIMA	37.74 ± 0.04
	FLUKA	40.34 ± 0.03

Depth profiles of the residual activity for both irradiation energies were simulated by FLUKA, taking into account exact experimental geometry. The number of the initial seeds for each case was 10^6 seeds.

RESULTS

The experimental stopping range of the primary ions was estimated by means of the truncated cylinder technique. The resolution of such method depends on the configuration of the target. The position of the trace in present experiment was found within 0.25 mm accuracy. The results are shown in Fig. 3 and Fig. 4 for 500 MeV/u and 950 MeV/u respectively.

While irradiating the target by ion beam two types of radioactive nuclides could be produced: (1) the products of target activation and (2) the projectile fragments. The target-like nuclei could be found in the whole target, while projectile fragments are only found in the range area. Gamma-analysis of individual thin foils was performed for studying the depth profiles of partial residual activities. There are not so many possibilities for the products of target activation, because aluminium is a light nucleus. Most of the nuclei lighter than aluminium are either too short-lived or they are not γ-emitters, thus they could not be detected by HPGe detector with the present experimental method. In this case only ^7Be and ^{22}Na can be detected. The uranium, on contrary, is a

heavy nuclei ($Z=92$), it has different possibilities for fragmentation, which makes analysis of the γ-spectra complicated because of the interfering γ-lines. Present paper gives experimental and simulated depth profiles of the nuclides, with the biggest contribution to the residual activity. The number of nuclides per incident ion per unit thickness is obtained. All the results are recalculated to the end of the irradiation.

The distribution of ^{237}U in depth could be used for finding the range of primary ^{238}U ions with 1.5% precision, because the masses of these nuclei are almost equal. The comparisons of experimental and simulated depth profiles of ^{237}U are shown in Fig. 3 and Fig. 4 for 500 MeV/u and 950 MeV/u respectively.

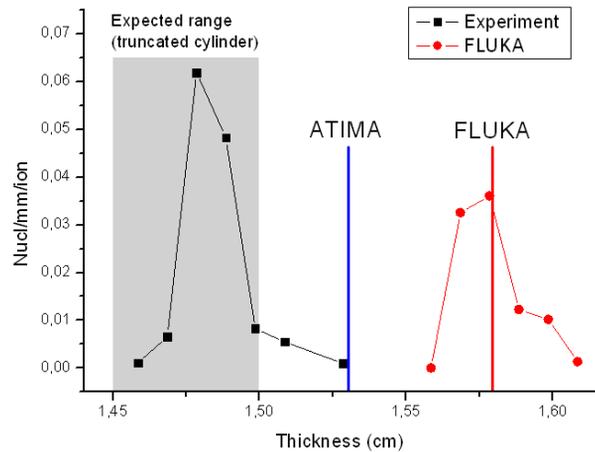


Figure 3: Comparison of the experimental and simulated stopping range of 500 MeV/u uranium ions in aluminium.

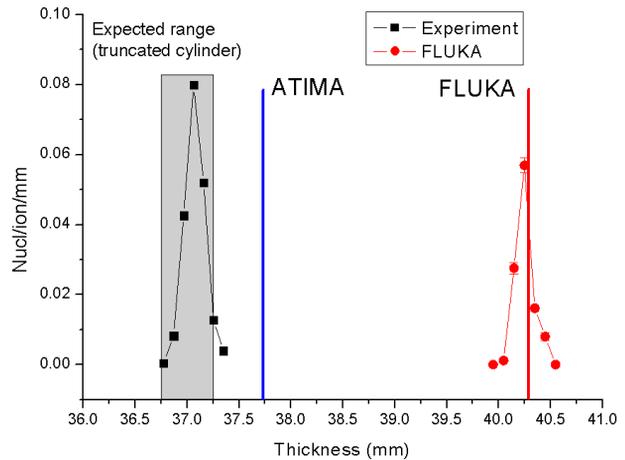


Figure 4: Comparison of the experimental and simulated stopping range of 950 MeV/u uranium ions in aluminium.

Figures 5 and 6 present the depth profiles of ^7Be . Depth profiles of ^{22}Na are presented in Figures 7 and 8. Both nuclei could be the products of target activation as well as the projectile fragments.

The products of target fragmentation in our study are the residual nuclei much heavier than aluminium, such as ^{237}U , ^{230}Pa , ^{232}Pa . The experimental results in comparison with simulations are shown in Figs. 9-12. The depth

profiles of ^{230}Pa and ^{232}Pa ($Z=91$) could also be used to control the correctness of the stopping range.

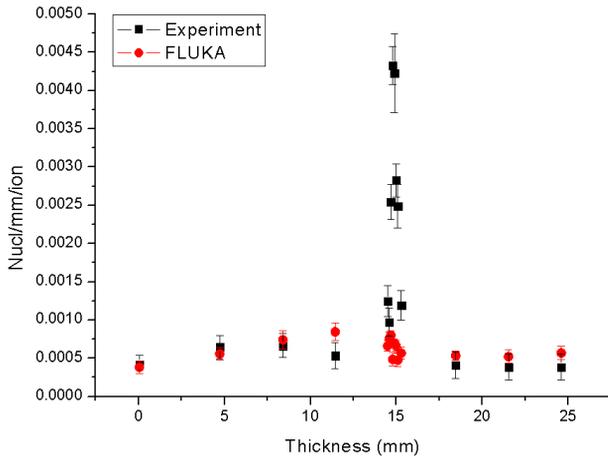


Figure 5: Experimental and simulated depth profile of ^7Be for 500 MeV/u incident uranium.

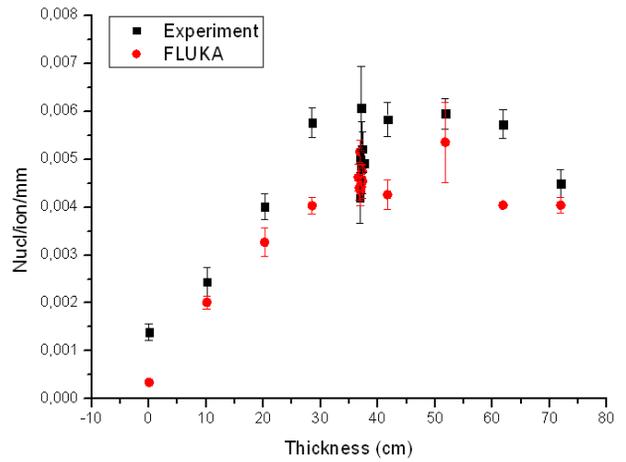


Figure 8: Experimental and simulated depth profile of ^{22}Na for 950 MeV/u incident uranium.

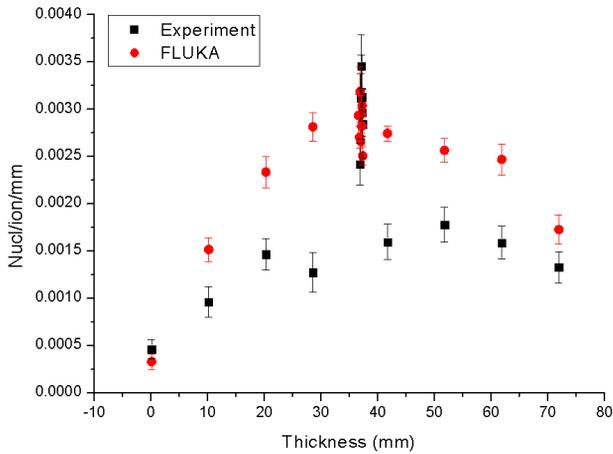


Figure 6: Experimental and simulated depth profile of ^7Be for 950 MeV/u incident uranium.

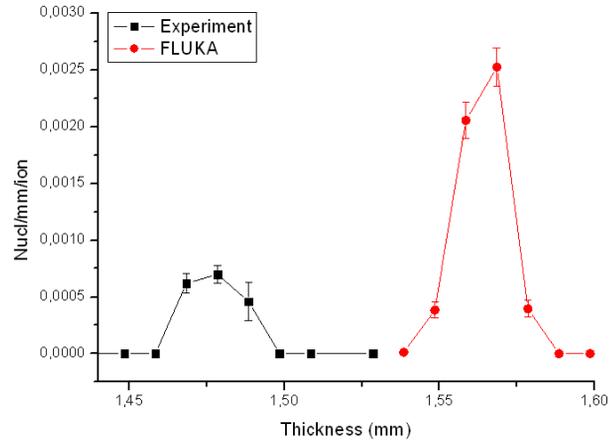


Figure 9: Experimental and simulated depth profile of ^{230}Pa for 500 MeV/u incident uranium.

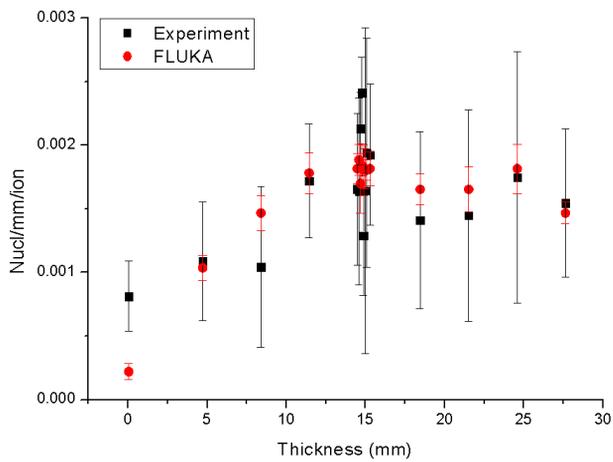


Figure 7: Experimental and simulated depth profile of ^{22}Na for 500 MeV/u incident uranium.

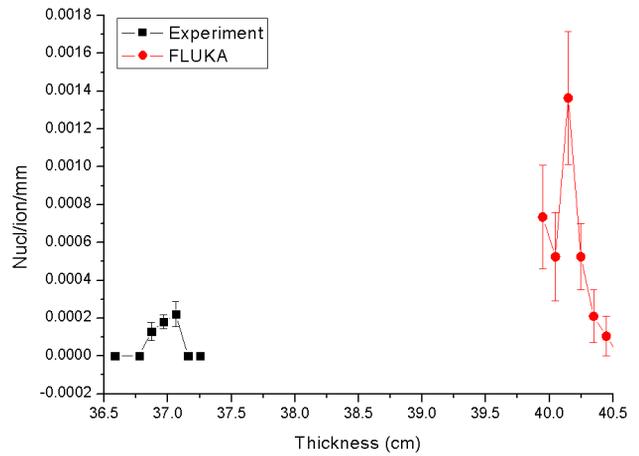


Figure 10: Experimental and simulated depth profile of ^{230}Pa for 950 MeV/u incident uranium.

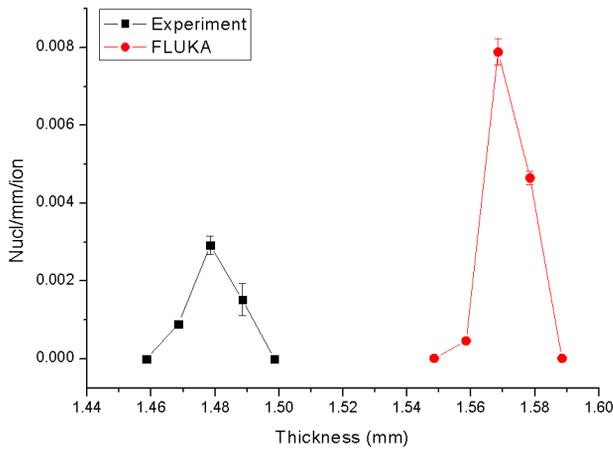


Figure 11: Experimental and simulated depth profile of ^{232}Pa for 500 MeV/u incident uranium.

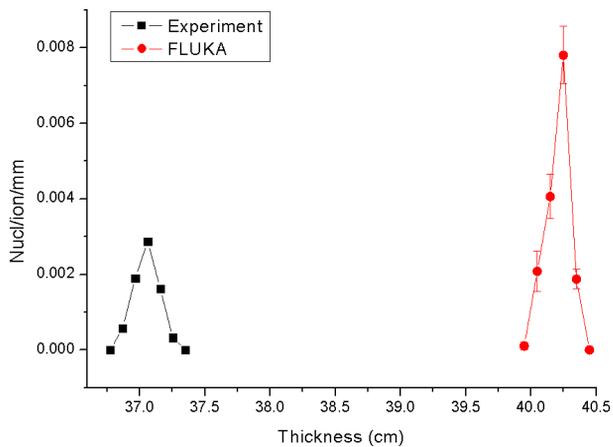


Figure 12: Experimental and simulated depth profile of ^{232}Pa for 950 MeV/u incident uranium.

DISCUSSION

By looking at the results of the measured and calculated stopping ranges (Figures 3 and 4) of uranium one can observe ~3% discrepancy of the ATIMA-simulations. FLUKA gives 7% and 10% larger values for 500 MeV/u and 950 MeV/u respectively. The same inconsistencies take place in simulating the position of the maximum of the production rate of heavy projectile fragments.

The depth profiles of ^{22}Na calculated by FLUKA are in a very good agreement with the experiment.

The origin of the discrepancies in the case of ^7Be is not clear. On one hand it could be a misinterpretation of the γ -line, on the other hand it could be because of the absence

of models in FLUKA, describing the nuclear interactions of ions ($A>1$) with energies below 100 MeV/u.

The comparison of FLUKA-calculated and experimentally measured depth profiles of projectile fragments shows inconsistencies. The number of ^{237}U per incident ion is underestimated by a factor of 2, while the number of ^{232}Pa and ^{230}Pa is larger by a factor of 2. As it could be seen from Figures 11 and 12, the production rate of ^{232}Pa does not depend on energy in this case.

CONCLUSION

The irradiation of aluminium targets by uranium ions of 500 MeV/u and 950 MeV/u was performed. The stopping range of primary ions and the depth profiles of the nuclides with the largest contribution to the residual activity are presented. The ranges calculated by ATIMA are in agreement with the experiment within the 3% error bar, FLUKA gives discrepancies of up to 10%.

The dependences of nuclides' production rates on depth are obtained. The depth profiles of the target-like nuclei are simulated by FLUKA with a good precision. In case of the projectile fragments discrepancies are observed.

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