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Activation of aluminum by argon: Experimental study and simulations

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ABSTRACT

The paper presents the results of irradiation of aluminum targets by 430 and 500 MeV/u argon beams. Gamma-spectra were measured after the end of the irradiation in order to identify the induced nuclides as well as to determine their residual activity depth-profiles. The results of this experiment are compared with Monte Carlo simulations by FLUKA, GEANT4, MARS, PHITS and SHIELD-A codes. In case of a thin target, the agreement between the experiment and simulations is satisfactory, while in case of a thick target, some discrepancies are observed.

1. Introduction

Activation studies of materials used for construction of accelerator components and corresponding radiation protection of accelerators are of great importance especially for machines with high beam intensities [1–3]. Information about nuclide distributions and induced partial activities of individual nuclides is also necessary to derive criteria for tolerable beam losses [4], to estimate activity levels in case of accidental beam losses and thus, to design the shielding needed to avoid unnecessary personnel exposure. Moreover, it will aid decisions on the maintenance strategy, that is, whether hands-on maintenance is at all possible or whether remote handling instrumentation is needed for individual components.

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. Stainless steel and copper were irradiated by $^{238}U^{+73}$ beams at 500 and 950 MeV/u [5,6] and copper was irradiated by $^{40}Ar^{+18}$ beams at 500 MeV/u and 1 GeV/u [7]. This paper presents a continuation of these experiments for aluminum irradiated by $^{40}Ar^{+18}$ beams having 430 and 500 MeV/u. Aluminum 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 the previous experiments [5–7]. Aluminum components should be preferred in accelerator areas with high beam losses (e.g. extraction region, beam-diagnostics components, etc.).

2. Experiment and methods

Two aluminum targets were irradiated in an experimental cave by the beam from the heavy-ion synchrotron SIS18 and transferred to a measurement room after the end of the irradiation. The gamma-spectra were acquired by a high-purity germanium (HPGe) detector inside a low-background container. The experimental and spectroscopic set-up was similar to the previous experiments

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[5–7]. Two types of targets were irradiated. A thin-foil target was used to study the residual activity and specifically the contribution of short-lived nuclides to the total activity. A thick target was used for depth-profiling of residual activities of individual nuclides.

2.1. Targets and irradiation conditions

The target material consisted of Al (99.2 wt.%), Si (0.25 wt.%), Fe (0.4 wt.%), Mn (0.05 wt.%), Cu (0.05 wt.%) and Mg (0.05 wt.%). The targets were irradiated by fast-extracted $^{40}Ar^{+18}$ beams with approximately Gaussian beam profile (FWHM ≅ 1 cm as measured using fiducials on a scintillation screen and a beam-profiler) at 430 and 500 MeV/u. The duration of the cycle was 3 s. The beam intensity was measured by a current transformer with 3% accuracy.

The thin-foil target was 0.1 ± 0.005 mm thick and 5 cm in diameter. Its thickness was chosen to be low enough to keep the dose rate below 3 μSv/h. Such a dose rate allows manual handling the target shortly after the end of the irradiation, which is important for measuring the short-lived nuclides. The thin-foil target was irradiated by 430 MeV/u argon beam. The total number of projectiles accumulated on the target was $2.38 \cdot 10^{14} \pm 6.65 \cdot 10^{10}$ ions.

The thick target was a cylinder assembled from thin activation foils and thick distance-making disks (spacers). The activation foils were used to get individual data-points for depth profiling by measuring the γ-spectra of their residual activity. The thick disks were used as spacers to define the depth-points of the profiles by keeping the distance between the activation foils. The target configuration is shown schematically in Fig. 1. The geometry (position and thickness of the foils and disks) is listed quantitatively in Table 1. The standard uncertainty of the thickness-data does not exceed 5% for each thin foil and 1% for each thick disk. The overall length of the target was 11.062 cm, the diameter of all foils and disks was 5 cm. This target was irradiated by 500 MeV/u argon beam with a total of $1.01 \cdot 10^{13} \pm 1.40 \cdot 10^{10}$ ions on the target. For assembling the target in an optimal way (a set of thin activation foils was placed in the range-region of the primary argon ions), the range was estimated by ATIMA 1.2 [8], FLUKA 2008.3b [9,10], MARS15 [11–15], SHIELD-A [16,17] and SRIM2008 [18] taking into account the energy loss in a 100 μm vacuum window and 1 m long air drift-space between the vacuum window and the target (the target-material-equivalent thickness was about 1 mm). The range and range straggling as calculated by the above-mentioned codes are shown in Table 2.

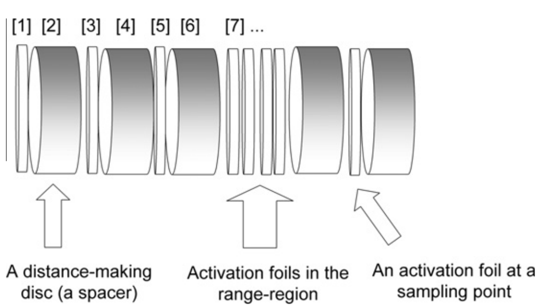

Fig. 1. Schematic arrangement of the thick target.

Table 1
Configuration of the thick target irradiated by 500 MeV/u argon beam.

Foil number	[1]	[2]	[3]	[4]	[5]	[6]	[7]
Foil thickness (cm)	0.1	1.402	0.1	1.401	0.1	1.389	0.1
Foil number	[8]	[9]	[10]	[11]	[12]	[13]	[14]
Foil thickness (cm)	1.388	0.1	0.1	0.1	0.1	0.1	0.1
Foil number	[15]	[16]	[17]	[18]	[19]	[20]	
Foil thickness (cm)	1.4	0.098	1.399	0.098	1.389	0.098	

2.2. Measurements

The gamma-ray spectra were measured by a coaxial high-purity germanium detector with 20% efficiency. The energy resolution of the detector was 0.9 and 1.9 keV at 122 keV and at 1.33 MeV, respectively. The energy range was from 30 keV up to 2 MeV. Energy and efficiency calibrations were done with a set of point-like sources: ^{137}Cs, ^{60}Co, ^{22}Na and ^{152}Eu. The fitting of the calibration curves was done with OriginPro 8. The following fit was obtained for the absolute efficiency of the spectrometer:

$$abs\_eff = 0.00722 \cdot e^{-\mathrm{Energy}/250.32058} + 18.91534 \cdot e^{-\mathrm{Energy}/4.45196.10^{7}} - 18.914 \quad (1)$$

The efficiency-calibration data-points together with the above fitting curve are shown in Fig. 2.

The first gamma-spectra acquisition of the thin-foil target started 96 min after the end of the irradiation in order to register also the short-lived nuclides. It was then followed by measurements in several later time points and stopped finally 2 weeks after the end of irradiation. The real time of the measurements varied from 5 min with 7% dead time for the first spectra up to 25 h with 0.1% dead time for the spectra acquired 2 weeks after the end of irradiation.

The thick target was used to study the depth profiles of the residual activities of individual nuclides. In this case, the induced activity was so high that removal of the target from the experimental cave was not possible shortly after the end of the irradiation due to radiation protection reasons. The thin activation foils (see Table 1) were used for gamma-spectroscopy. Three series of measurements were performed: 28–40 days, 49–69 days and 89–95 days after the end of irradiation. The duration of each single-foil measurement was about 24 h with dead time below 1%.

3. Experimental results and comparison with simulations

3.1. Thin-foil target

For having an overview about the type and amount of the nuclides that can be produced in the thin-foil 99.2% aluminum target irradiated by argon beam at 430 MeV/u, FLUKA simulations were run. The results – the number of nuclides produced by one incident ion per unit thickness at the end of irradiation – are presented in Table 3. Most of the listed nuclides are too short-lived with respect to the time point of the earliest possible measurement (half life below 30 min), or are not γ-emitters or both, thus their presence could not be verified in the present experiment. The only nuclides that could be registered are ^{7}Be, ^{22}Na, ^{24}Na, ^{52}Mn and ^{58}Co. ^{58}Co was below the minimum detectable activity (MDA) of 10 Bq determined from the earliest (96 min after the end of irradiation) mea-

Table 2
Calculated ranges and range straggling of Ar ions in Al (initial energy 500 MeV/u, energy losses in vacuum window and air gap taken into account).

Computer code	ATIMA 1.2	FLUKA2008.3b	MARS15	SHIELD-A	SRIM 2008
Range ± straggling (cm)	6.748 ± 0.011	6.840 ± 0.022	6.953 ± 0.011	6.675 ± 0.005	6.612 ± 0.236