# Activation by 2.25 and 3.36 GeV electrons: Comparison of measurements with FLUKA calculations

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**Abstract**

*Activation of materials impacted by GeV electron beams at particle accelerator facilities is of great importance for the purposes of radiation protection as well as decommissioning. In order to measure common material activation in the beginning and well inside an electromagnetic cascade, Al, Cu, Nb, Pb, and stainless steel foils (0.01 – 0.1 mm) were placed upstream and downstream of 1.25 cm thick tungsten alloy plates and irradiated by 2.25 and 3.36 GeV electron beams. Gamma spectroscopy analysis of each foil was then performed using high purity germanium detectors. The measured activities were compared to the values calculated using FLUKA Monte Carlo code. A good overall agreement was shown for the foils placed inside well-developed cascades, while activation in the beginning of the cascades was generally underestimated. The underestimation was corrected by the introduction of a simplified model of electronuclear interaction based on the equivalent photon approximation.*

## Introduction

One of the most important concerns of radiation safety programmes at high-energy electron accelerator facilities is induced radioactivity. It typically presents the most significant source of occupational exposure and must also be considered from the points of view of environmental impact, material disposal, and facility decommissioning [1]. Most radioactivity at electron accelerators is produced by the photonuclear reactions and by the secondary radiation, such as neutrons. However, in thin targets (thicknesses of less than a few percent of a radiation length) the electronuclear interaction is a significant source of activation.

The purpose of this work was to measure activation of commonly used metals in the beginning and in the middle of electromagnetic showers produced by GeV electrons and to compare the measurement results with the values predicted using FLUKA Monte Carlo code [2]. FLUKA is widely used to calculate radionuclide inventories produced by the photonuclear reactions and by the interaction of secondary particles, but does not currently include the electronuclear interaction mechanism.

Opportunity to irradiate samples presented itself when a nuclear physics experiment was designed to measure the proton's transverse spin structure function $g^p_2$ planned to terminate 2.25 and 3.36 GeV electron beams on a specially designed tungsten alloy dump. Two stacks of Al, Cu, Nb, Pb, and type 316L stainless steel foils were placed in special cartridges on the face of the dump, separated from each other by a 1.25 cm thick tungsten alloy plate. The front foils were irradiated by early stages of electromagnetic showers and the back foils saw well-developed cascades.

Activated foils were then analysed in series of gamma spectroscopy measurements using high-purity germanium detectors. The measurement results were compared to FLUKA calculations. Both 2.25 and 3.36 GeV irradiations were modelled twice: first using the standard FLUKA distribution and then by introducing a simplified model of the electronuclear interaction based on the equivalent photon approximation [3].

## Methods and materials

The sample irradiation took place at Jefferson Lab's experimental Hall A during the $g^p_2$ experiment. Two separate irradiations used 2.25 and 3.36 GeV electron beams with 2 cm diameter circular rastering.

After passing through a liquid ammonia target, the electrons were bent in magnetic field and exited the target chamber through a 0.58 mm thick Al window with $6^0$ and $4^0$ angles, respectively. Then they travelled through 18 cm of helium gas and were incident on the first stack of foils, followed by a 1.25 cm thick HD17 tungsten alloy plate (90% W, 6% Ni, 4% Cu) and the second stack of foils. One cm downstream from the back foils, the beams were absorbed by a 10 cm long HD17 dump surrounded with lead shielding. Schematic representation of the experimental set-up is presented in Figure 1 and the irradiation profile in Figure 2. The two stacks consisted of 0.1 mm Al, 0.1 mm Cu, 0.1 mm Nb, 0.05 mm Pb, and 0.1 mm steel 316L, and 0.01 mm Al, 0.01 mm Cu, 0.01 mm Nb, 0.025 mm Pb, and 0.025 mm steel 316L foils, respectively.

Several hours after the end of each irradiation, the foils were transported to the radioanalytical laboratory where series of gamma spectroscopy analysis were performed during the following 3 months. The foils were analysed using high-purity germanium detectors and GENIE-2000 software [4]. The absolute detector efficiency for each sample was calculated using ISOCS™ software [5]. Each foil was counted 4 to 7 times with count times varying from 10 minutes to 24 hours. The short counts taken relatively soon after the irradiation were used to measure the short-lived radioactivity, while the longer counts taken later in time were used to measure the long-lived radionuclides. The pulse height spectra were thoroughly analysed, including the use of specially compiled nuclide libraries, performing cascade corrections, and various quality control and quality assurance techniques.

**Figure 1. Schematic representation of the experimental set-up**

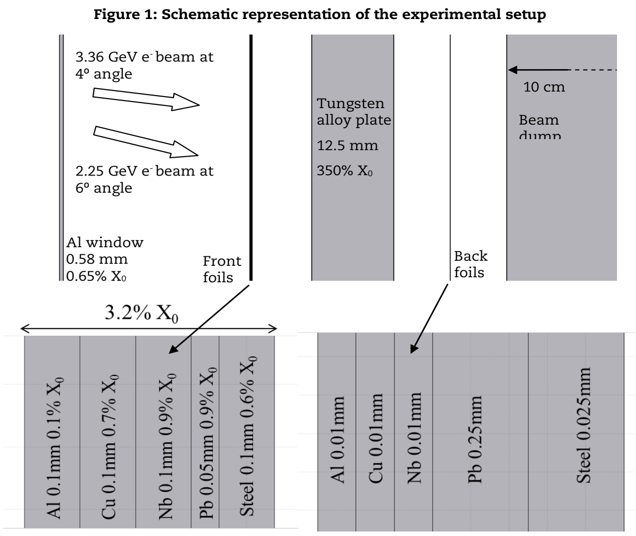
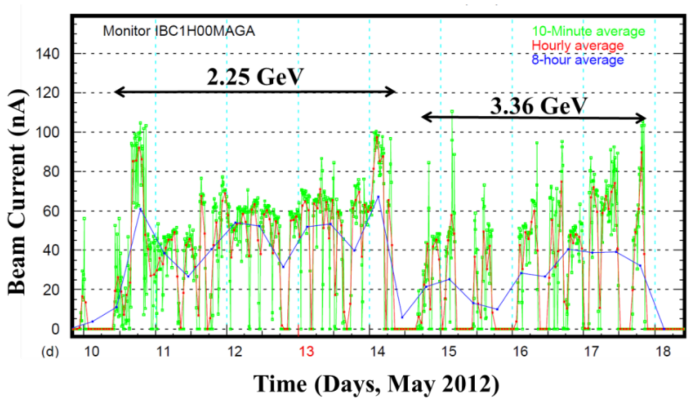


**Figure 2. Irradiation profile**




Detailed models of the foil irradiations were created using FLUKA. Radionuclide inventories were calculated for the decay times corresponding to the gamma spectroscopy measurements. The first set of FLUKA calculations modelled interaction of monoenergetic electron beams with the targets, hence not taking into consideration the electronuclear interaction mechanism. In the second set of the calculations, a FLUKA source routine was used to introduce a simplified model of the electronuclear interaction based on the equivalent photon approximation [3].

## Results

The comparisons of measured activities to the values calculated using FLUKA are presented in Figures 3-12. Figures 3, 5, 7, 9, and 11 present the comparisons with the main FLUKA distribution results, not including the electronuclear interactions. Figures 4, 6, 8, 10, and 12 present the results that include the electronuclear correction introduced in FLUKA via the source routine.

$^{91m}$Nb in Figures 7 and 8 and $^{202m}$Pb in Figures 9 and 10 are not shown. Production of these metastable states of Nb and Pb isotopes was overestimated by factors of 4.2 and 4.4 on average in the back foils. In the front foils, they were overestimated by factors of 1.2 and 2.2 on average. The addition of the electronuclear model changed these values to 1.7 and 3.8, respectively.

**Figure 3. Comparison of Al activation with FLUKA calculation**

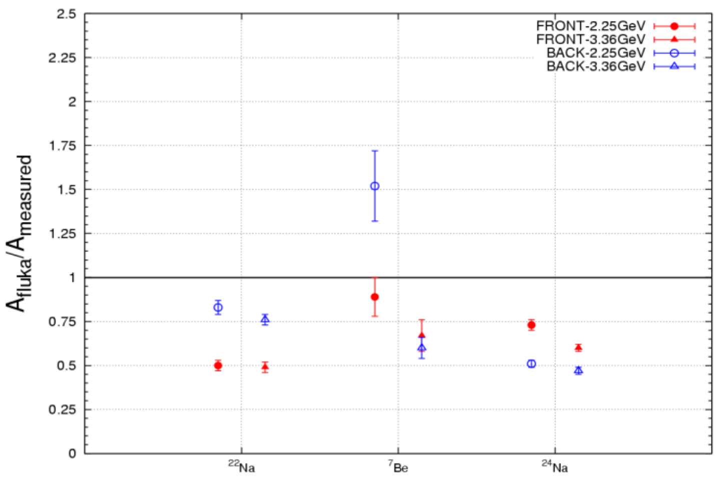


**Figure 4. Comparison of Al activation with FLUKA calculation performed using a source routine accounting for the electronuclear interaction**

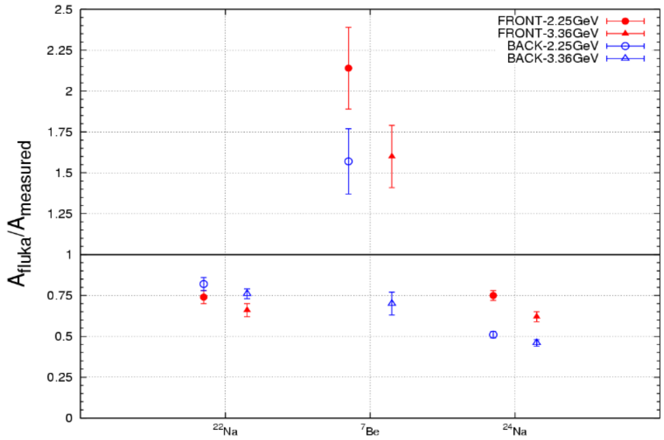



**Figure 5. Comparison of Cu activation with FLUKA calculation**

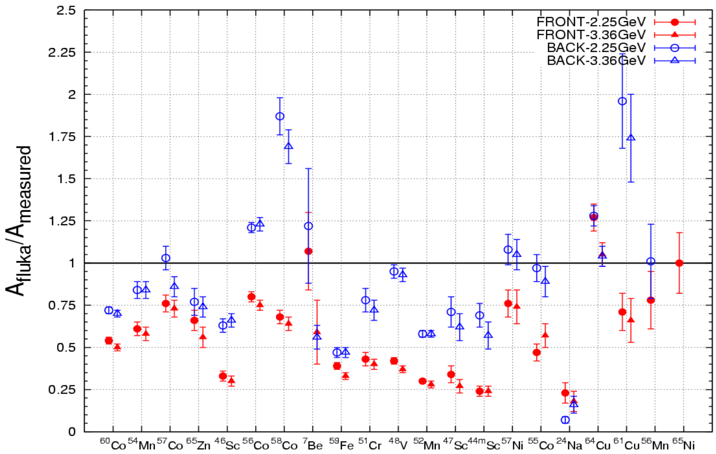



**Figure 6. Comparison of Cu activation with FLUKA calculation performed using a source routine accounting for the electronuclear interaction**

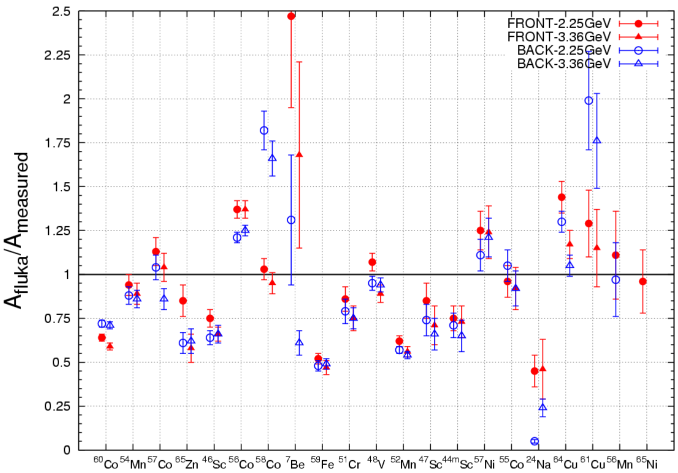


**Figure 7. Comparison of Nb activation with FLUKA calculation**

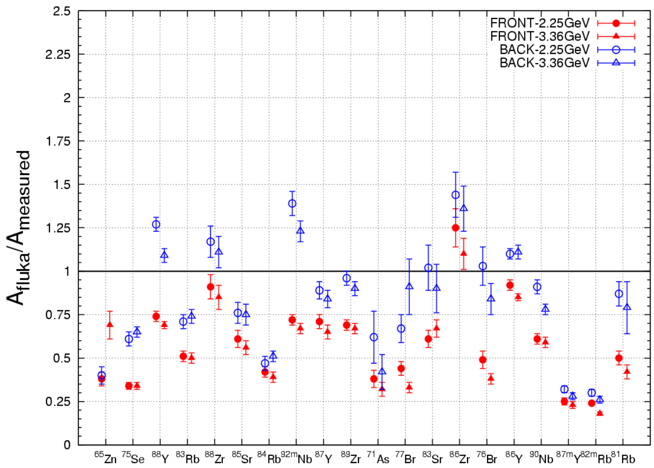



**Figure 8. Comparison of Nb activation with FLUKA calculation performed using a source routine accounting for the electronuclear interaction**

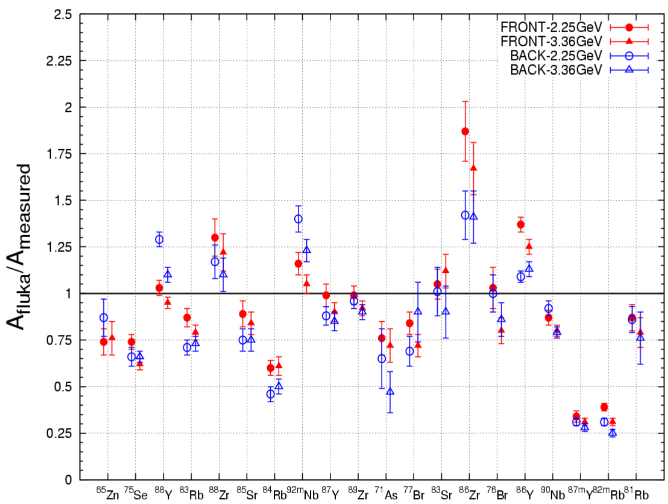



**Figure 9. Comparison of Pb activation with FLUKA calculation**

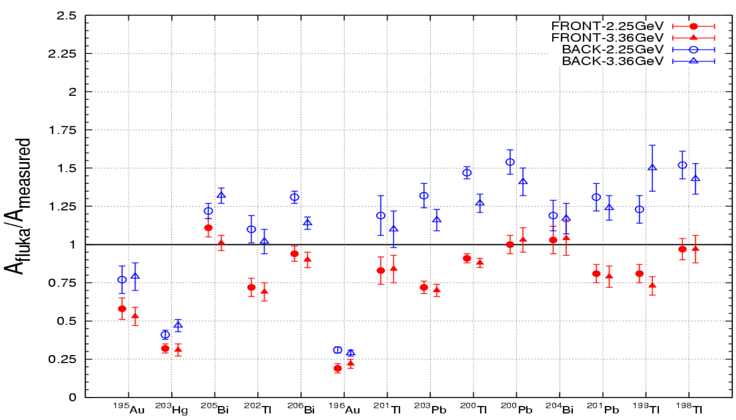


**Figure 10. Comparison of Pb activation with FLUKA calculation performed using a source routine accounting for the electronuclear interaction**

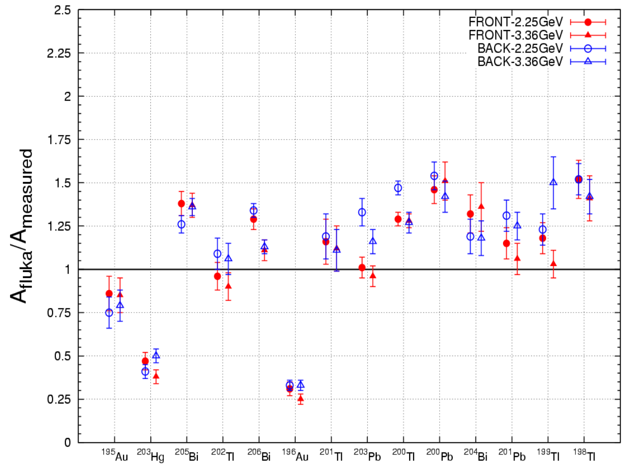



**Figure 11. Comparison of steel 316L activation with FLUKA calculation**

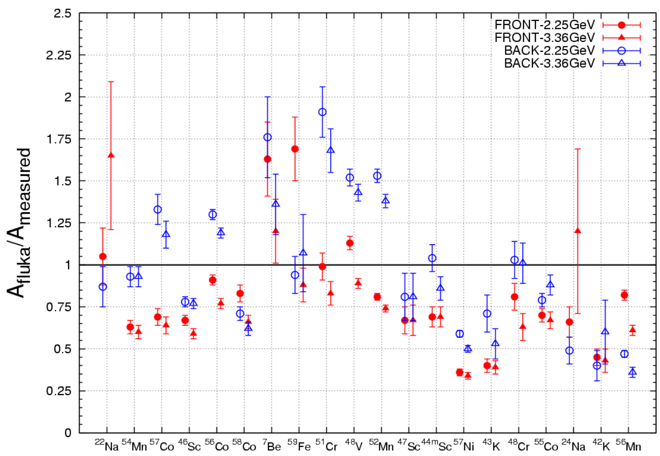
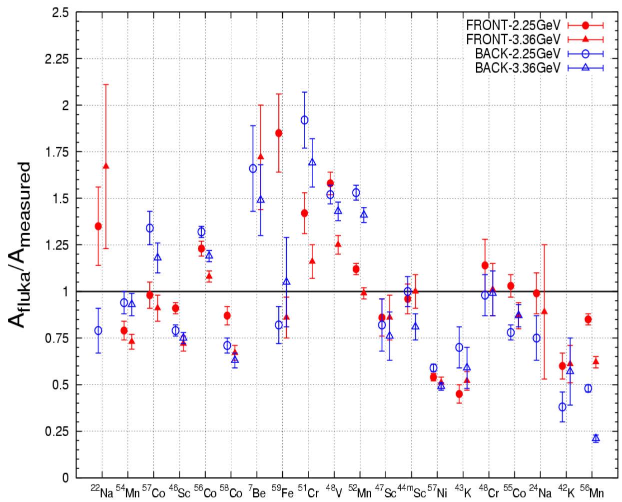



**Figure 12. Comparison of steel 316L activation with FLUKA calculation performed using a source routine accounting for the electronuclear interaction**



## Conclusions

Activation of Al, Cu, Nb, Pb, and stainless steel foils in the beginning and in the middle of the electromagnetic showers produced by 2.25 and 3.36 GeV electron beams was measured. Results were compared to FLUKA calculations performed with and without a source routine written to account for the electronuclear interactions.

A good overall agreement of FLUKA with the experiment was demonstrated in the back foils, which were exposed to well-developed electromagnetic showers. Exceptions were $^{91m}$Nb and $^{202m}$Pb, which were overestimated 4 – 4.5 times. The overestimation of these isomers may be attributed to the simplistic approach of equal sharing used in FLUKA. The present models do not distinguish between ground state and isomeric states and instead evenly populate them.

A systematic underestimation of activation in the front foils was observed when the electronuclear interactions were not considered. The introduction of the model based on the equivalent photon approximation corrected the underestimation for the majority of the detected radionuclides.

## Acknowledgements

The authors would like to thank Alberto Fassò, Vashek Vylet, Adam Hartberger, David Hamlette, Keith Welch, Maya Keller, Jixie Zhang, Alan Gavalya, Ed Folts, Karl Slifer, J. P. Chen, and g2p collaboration for their contributions. This work was supported by the US Department of Energy under contract number DE-AC05-06OR23177s.

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