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Measurements and FLUKA simulations of bismuth and aluminium activation at the CERN Shielding Benchmark Facility (CSBF)

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ABSTRACT

The CERN High Energy AcceleRator Mixed field facility (CHARM) is located in the CERN Proton Synchrotron (PS) East Experimental Area. The facility receives a pulsed proton beam from the CERN PS with a beam momentum of 24 GeV/c with $5{\cdot}10^{11}$ protons per pulse with a pulse length of 350 ms and with a maximum average beam intensity of $6.7{\cdot}10^{10}$ p/s that then impacts on the CHARM target.

The shielding of the CHARM facility also includes the CERN Shielding Benchmark Facility (CSBF) situated laterally above the target. This facility consists of 80 cm of cast iron and 360 cm of concrete with barite concrete in some places.

Activation samples of bismuth and aluminium were placed in the CSBF and in the CHARM access corridor in July 2015. Monte Carlo simulations with the FLUKA code have been performed to estimate the specific production yields for these samples. The results estimated by FLUKA Monte Carlo simulations are compared to activation measurements of these samples.

The comparison between FLUKA simulations and the measured values from γ-spectrometry gives an agreement better than a factor of 2.

1. Introduction

The CERN High Energy AcceleRator Mixed field facility (denoted CHARM) has been constructed in the CERN Proton Synchrotron (PS) East Experimental Area in 2014 [1]. The facility receives a pulsed proton beam from the CERN PS with a beam momentum of 24 GeV/c with $5{\cdot}10^{11}$ protons per pulse with a pulse length of 350 ms and with a maximum average beam intensity of $6.7{\cdot}10^{10}$ p/s [2] with a minimum pulse spacing of 2.4 s.

The extracted proton beam from the PS impacts on a cylindrical copper or aluminium target and the created secondary radiation field is used to test electronics equipment installed at predefined test positions [3].

The shielding of the CHARM facility [4] also includes the CERN Shielding Benchmark Facility (CSBF) situated laterally above the target [5]. This facility allows deep-penetration benchmark studies of various shielding materials.

Activation samples of bismuth and aluminium can be used for the measurement of high-energy neutrons [6]. In order to characterize the radiation fields in the CSBF such samples were placed in the CSBF and in the CHARM access corridor in July 2015. Monte Carlo simulations with the FLUKA code [7,8] have been performed to estimate the specific production yields of several bismuth isotopes and sodium-24 for these samples. This paper describes the comparison between the estimated values from FLUKA and the activation measurements performed in July 2015 with bismuth and aluminium disc samples of different sizes in the CSBF and in the CHARM access corridor.

2. Beam parameters and configurations

This section presents the beam parameters and the facility configurations that were used during the activation experiments. The beam intensity was measured with a Secondary Emission Chamber, denoted SEC1,

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Table 1
Chemical composition and density of concrete [10].

Concrete	Density 2.4 g/cm^3		
Element	Weight fraction (%)	Element	Weight fraction (%)
Hydrogen	0.561	Silicon	16.175
Carbon	4.377	Sulphur	0.414
Oxygen	48.204	Potassium	0.833
Sodium	0.446	Calcium	23.929
Magnesium	1.512	Titanium	0.173
Aluminium	2.113	Iron	1.263

Table 2
Chemical composition and density of barite concrete [11].

Barite concrete	Density 3.35 (g/cm^3)
Element	Weight fraction (%)
Aluminium	0.418
Barium	46.34
Calcium	5.019
Iron	4.751
Hydrogen	0.358
Magnesium	0.12
Oxygen	31.162
Sulphur	10.786
Silicon	1.046

Table 3
Chemical composition [12] and density of cast iron [10].

Cast iron	Density 7.2 g/cm^3
Element	Weight fraction (%)
Iron	92.3
Carbon	3.85
Manganese	0.3
Silicon	3.4
Phosphorus	0.08
Sulphur	0.02
Cobalt	0.05

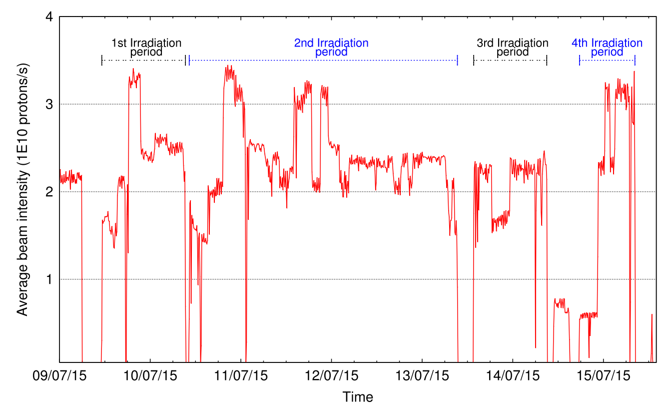

Fig. 1. Average beam intensity of the CHARM facility during the activation experiments with binning of 10 min long intervals.

whose measurement values are logged in the measurement database, TIMBER. An intensity calibration factor of $1.87 \cdot 10^7$ protons/count has been applied to the counts per pulse to obtain the number of protons per pulse. This calibration factor had been obtained with aluminium foil activation using sodium isotopes with a statistical uncertainty of 7% from the γ-spectrometry measurement [9].

A beam size of 1.2 cm × 1.2 cm Full Width at Half Maximum (FWHM) was used for the FLUKA simulations as specified in the layout of the beam line and confirmed with online beam profile measurements [9].

The average beam intensity of CHARM, binned in 10 min long intervals, from July 9 to July 15, 2015 when the experiments were conducted, is shown in Fig. 1. The 4 different irradiation periods used during the activation measurements are also indicated in Fig. 1.

The beam passes through the upstream IRRAD facility before impacting on the CHARM target. During the period of the experiment, Silicon samples with a total thickness of 0.2 cm were placed into the beam in IRRAD and this was also taken into account in the FLUKA simulations.

The shielding layout of the CSBF is shown in Fig. 2. The chemical composition of the concrete, the barite concrete and the cast iron implemented in the FLUKA Monte Carlo simulations for the shielding with their respective densities are listed in Table 1, in Table 2 and in Table 3.

During the activation experiment, the cylindrical copper target of 8 cm diameter and 50 cm length has been used inside the CHARM facility. Inside the target room there are four movable shielding walls, each of 20 cm thickness and made out of concrete and iron. They can be placed between the target and the irradiation positions in the CHARM facility in varied arrangement, so that the test spectra are adjusted to the desired radiation field (energy and intensity) during the tests. The movable shielding walls are presented in Fig. 3. For this activation experiment, two different configurations of the four movable shielding walls were used during the different irradiation periods, i.e all movable shielding walls retracted from the facility or all movable shielding walls inside the facility. The configurations have been properly taken into account in the FLUKA Monte Carlo simulations.

3. Samples and locations

Eleven disc samples in total, six bismuth samples and five aluminium samples, have been irradiated. Of these samples, five bismuth samples and four aluminium samples were placed in the CSBF at different heights and one bismuth sample and one aluminium sample inside the CHARM facility access corridor. All the details of the samples including their location, irradiation time, dimensions, weight, time of measurements are presented in Table 4.

The irradiation of the samples in the CSBF has been performed with the four movable shielding walls retracted from the facility. On the other hand, when the samples were placed inside the CHARM facility access corridor, the four movable shielding walls were inside the facility.

The irradiation positions of the samples in the CSBF and also inside the CHARM facility access corridor are illustrated in Figs. 2 and 3.

4. Simulations and measurements results

The simulation results were obtained by first scoring the neutron fluence spectra in the activation sample volumes with FLUKA. A detailed description of the models and cross section data used in FLUKA can be found in [7,8]. Then the neutron fluence was weighted with cross section data for the bismuth isotopes and sodium-24 [13], shown in Fig. 4, to obtain the predicted production yields per atom per primary proton on the target.

The activities of the bismuth isotopes and sodium-24 were measured for the bismuth and aluminium samples respectively using γ-spectrometry, sometimes even at different cool-down times. In case of multiple γ-spectrometry measurements of the same sample, the activities selected were the ones with the lowest uncertainty of the γ-spectrometry measurements. These activities have been converted to the production yields by taking into account the corresponding irradiation profiles with 10 min long binning and the corresponding cool-down times.

The production yields predicted by FLUKA and measured by γ-spectrometry are presented in Fig. 5, Fig. 6 and in Table 6. The agreement between FLUKA predictions and γ-spectrometry measurements for the production yields is better than a factor of 2. This is illustrated in Figs. 7 and 8.