

# INDUCED RADIOACTIVITY OF THE SEPTUM MAGNET OF THE BEAM SLOW EXTRACTION AT THE NUCLOTRON

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## Abstract

Calculation results are presented of the induced gamma radioactivity levels of the septum magnet of the NUCLOTRON slow extraction for the protons, deuterons and  $^{12}\text{C}$ ,  $^{56}\text{Fe}$ ,  $^{207}\text{Pb}$  nuclei with the energy 5 GeV/nucleon. Projectile particle, secondary hadron and projectile nucleus fragment contributions to the dose rate of induced gamma radiation for the septum magnet are calculated. The data obtained by Monte Carlo and our experiment are compared and discussed. It is shown that for heavy primary nuclei the main contribution to the septum induced radioactivity is caused by the projectile nucleus fragments and secondary hadrons. The maximum dose rate of the induced gamma radiation corresponds to the deuteron extraction for maximum beam intensities from  $10^{12}$  (deuterons) up to  $10^9$  (Pb nuclei) particle/second.

## 1 INTRODUCTION

In the nearest two years the production of external beams is the major problem for the NUCLOTRON accelerator development. The beam extraction system will be able to extract the beams over the range of energies from 200 MeV/amu up to 6 GeV/amu with the coefficient of extraction up to 90% [1]. The slow extraction system is described in [2, 3].

Induced radioactivity brings the main contribution to the dose for the personnel of a high energy accelerator. The present study deals with the levels of induced  $\gamma$ -radioactivity of the septum magnet, where the most portion of the particle losses is located.

## 2 SIMULATION TECHNIQUE

In this study the direct simulation of induced gamma radioactivity by the Monte-Carlo method is used, which can be split, schematically, into the following stages.

At first, the spatial-energetic distributions of the inelastic nuclear interactions for primary particles, secondary hadrons and projectile nucleus fragments are simulated separately with the use transport code EDMONT [4].

At the second stage, the cross sections  $\sigma_A$  of the production of radioactive isotopes in a nuclear interaction are calculated for hadrons with the semi-empirical Silberberg-Tsao's formulae [5] and for nuclei with atomic weight  $A$  – in the following way [6]:

$$\sigma_A = N \cdot \sigma_p,$$

$$N = A^{0.25} + (A-1)^{0.6} \cdot 0.078 (\ln A_T - 1.85).$$

In these relationships  $\sigma_p$  is the cross section of a radionuclide generation for a proton-nucleus collision and  $A_T$  is the atomic weight of the target nucleus.

At the final stage, the induced  $\gamma$ -source is defined from the generation and decay of the activities, and dose rates are calculated at various points around the target according to the algorithm [7].

The capability demonstration of the code package, developed for the calculation of the radioactivity induced by high energy protons and nuclei, is presented in [8, 9].

## 3 EXPERIMENTAL TESTS

To test our simulation technique, the septum was modelled by the tantalum plate with dimensions  $60 \times 150$  mm<sup>2</sup> and thickness 300  $\mu\text{m}$ , which was irradiated with protons of energy 1 GeV during 1 hour at the JINR Synchrophasotron. The irradiation control was performed with the activation detectors using the reactions  $^{27}\text{Al}(p,x)^{18}\text{F}$  and  $^{27}\text{Al}(p,x)^{24}\text{Na}$ . The monitoring inaccuracy did not exceed 10%. The primary proton flux determined with this method was  $(1.9 \pm 0.2) \times 10^8$  cm<sup>-2</sup>·s<sup>-1</sup>. The dose rate values of the induced  $\gamma$ -radiation were measured with the use of end-window counter. The error of the  $\gamma$ -radiation dose rate had the systematic nature and was less than 15%. Figure 1 illustrates the experimental configuration.

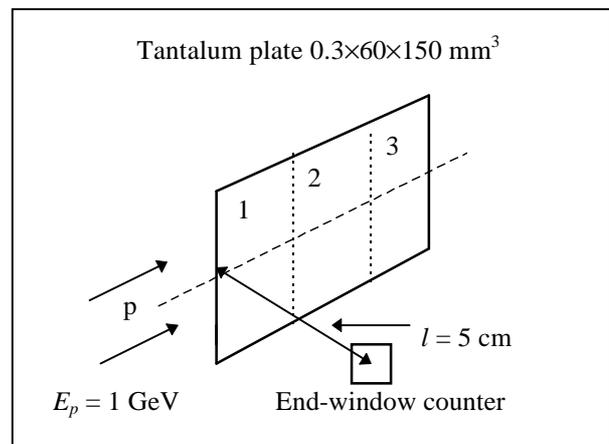


Figure 1. Geometry of the target irradiation and dose rate measurements.

Figure 2 shows the experimental data and simulation results of the dose rates per unit projectile flux in dependence on cooling time  $t$  at  $l = 5$  cm for the irradiated tantalum plate. The simulation results are obtained for the generated  $\gamma$ -radioactive nuclides with the half-life more than 5 minutes. At the activation of heavy metals, the contribution of the nuclides with the half-life less than 5 minutes is more than 90% of the dose rate for small  $t$  (for instance, for Cu) and less than 20% for large  $t$  [10]. Taking this into account, one can explain the 20-time underestimation of the dose rate values according to our calculation technique for simulation of the short-life component of the induced radioactivity.

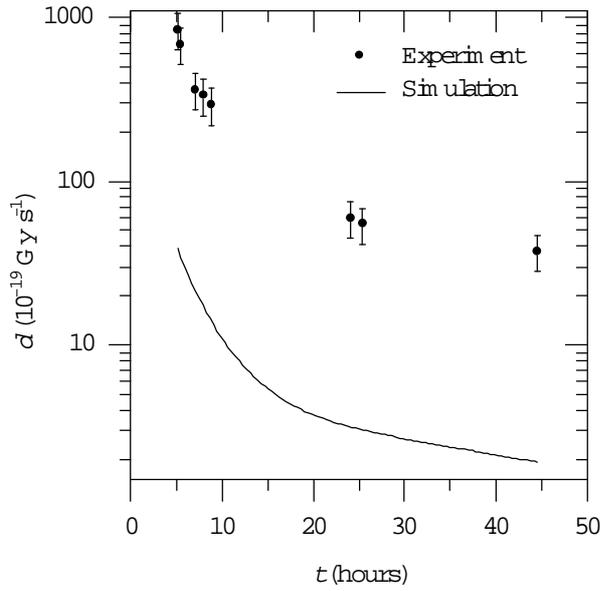


Figure 2. Experimental and simulation results of dose rates for the tantalum plate (see figure 1) at  $l = 5$  cm.

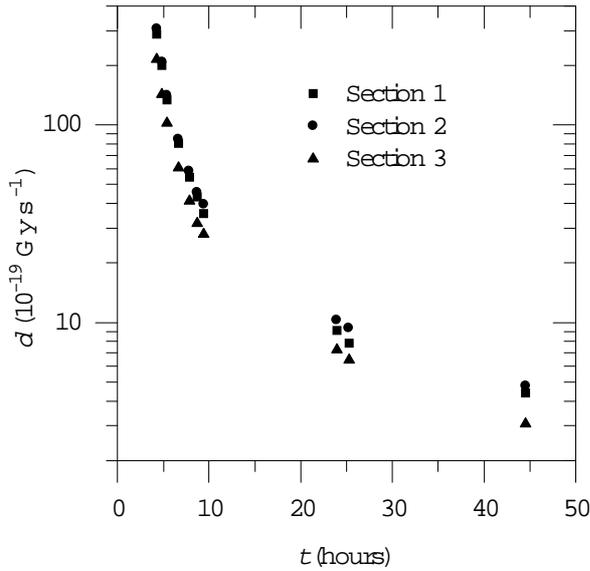


Figure 3. Experimental results of dose rates for three sections of the tantalum plate at  $l = 11$  cm (the error is not shown).

After that, this plate was snipped on three equal sections, numbered as it is shown at figure 1, and the dose rates were separately measured with the use of the end-window counter for those ones at  $l = 11$  cm. The obtained results per unit projectile flux, presented on figure 3, show that the total length 15 cm is long enough to model the septum by our plate.

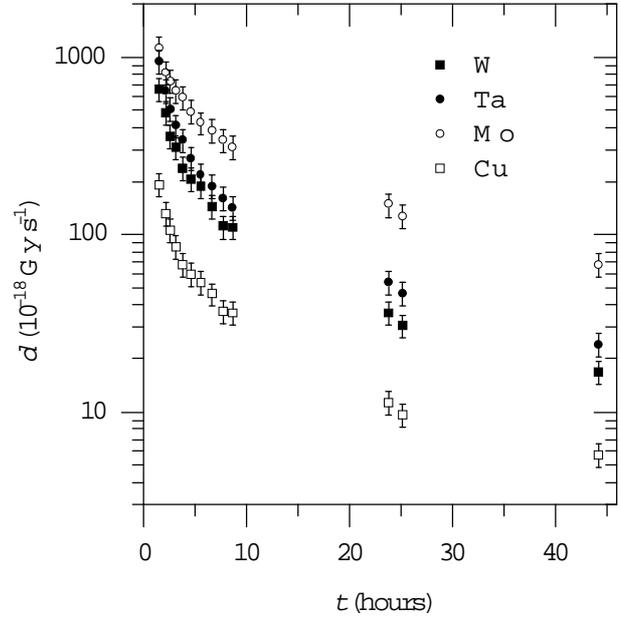


Figure 4. Experimental values of dose rates for the refractory metals at  $l = 11$  cm.

Also the tungsten, tantalum, molybdenum and copper thin targets were irradiated with proton beam of energy 8.1 GeV during 36 minutes at the JINR Synchrophasotron. The experimental conditions of the irradiation and dose rate measuring are the same as those described above. The sample characteristics and the total numbers  $G$  of incident protons for samples are presented in table 1.

Table 1. Weights, cross areas of the samples and numbers of incident protons.

Material	Weight, g	Area, cm <sup>2</sup>	$G$ , $10^{12}$
W	2.96	0.76	$0.40 \pm 0.04$
Ta	4.80	0.79	$5.9 \pm 0.6$
Mo	2.49	0.88	$0.34 \pm 0.04$
Cu	1.50	1.89	$9.2 \pm 1.0$

Experimental results, presented at figure 4, are the time-dependent dose rates per one incident proton by the induced  $\gamma$ -radioactivity of these samples at  $l = 11$  cm. The indicated error is the monitoring inaccuracy. It is shown that tungsten can be chosen for the design of septum as the least activated metal from all the studied refractory materials.

## 4 RESULTS AND DISCUSSION

The results, presented in figure 5, are the induced gamma radioactivity levels from the tungsten  $0.03 \times 6 \times 300 \text{ cm}^3$  deflection plate of the septum magnet of the NUCLOTRON slow extraction for the proton, deuteron and  $^{12}\text{C}$ ,  $^{56}\text{Fe}$ ,  $^{207}\text{Pb}$  nucleus irradiations with the energy 5 GeV/nucleon. The shown values  $d$  are the dose rates per unit primary flux and are obtained at 5 cm from plate point of beam inlet (see figure 1) for irradiation time 5000 days and  $t = 0$ .

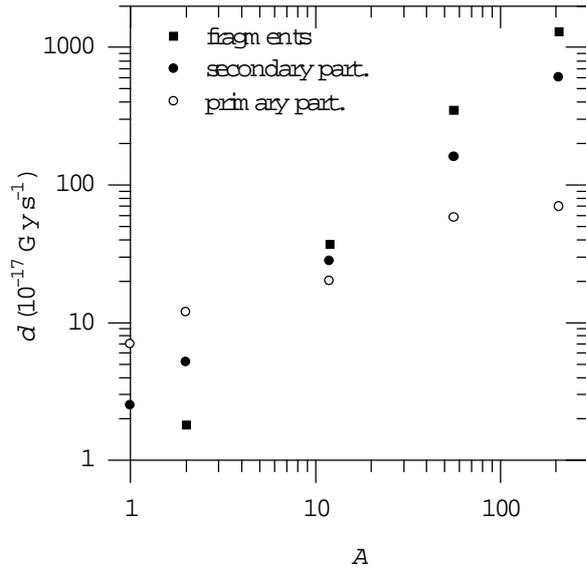


Figure 5. Contributions of the primary particles, secondary hadrons and projectile nucleus fragments to the dose rates of septum induced  $\gamma$ -radioactivity.

Contributions to the dose rate from the primary particles, the secondary hadrons and the projectile nucleus fragments are shown. For this target these contributions are equal for  $^{12}\text{C}$  nuclei and the projectile nucleus fragment contribution is the major for  $^{56}\text{Fe}$  and  $^{207}\text{Pb}$  nuclei. For the proton and deuteron irradiations the induced radioactivity is caused by the primary particles. Dependence of  $d$  on atomic weight  $A$  of primary nucleus is approximately linear.

Levels of the induced  $\gamma$ -radioactivity  $D$  at septum of the slow extraction system, presented in table 2, are calculated for irradiation time 5000 days,  $t = 0$  and maximum intensities  $I$ , obtained by the spatial charge limit. Contributions of the radionuclides with the half-life less than 5 minutes are not accounted. The maximum dose rate of induced  $\gamma$ -radiation will correspond to the deuteron extraction for the maximum possible intensities from  $10^{12}$  (deuterons) up to  $10^9$  (Pb nuclei) particles/second.

## 5 ACKNOWLEDGMENTS

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Table 2. Levels of the induced  $\gamma$ -radioactivity at septum of the slow extraction system.

Particle	$I, \text{s}^{-1}$	$d, \text{Gy} \cdot \text{s}^{-1}$	$D, \text{Gy} \cdot \text{s}^{-1}$
p	$5 \times 10^{11}$	$8.2 \times 10^{-17}$	$1.6 \times 10^{-6}$
d	$10^{12}$	$1.7 \times 10^{-16}$	$6.8 \times 10^{-6}$
$^{12}\text{C}$	$10^{11}$	$8.4 \times 10^{-16}$	$3.4 \times 10^{-6}$
$^{56}\text{Fe}$	$6.4 \times 10^9$	$5 \times 10^{-15}$	$1.3 \times 10^{-6}$
$^{208}\text{Pb}$	$1.5 \times 10^9$	$1.8 \times 10^{-14}$	$1.1 \times 10^{-6}$

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