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Secondary particle distributions in an extended uranium target under irradiation by proton, deuteron, and carbon beams

J. Adam [a,b], A.A. Baldin [a,c], M. Baznat [a,h], A.I. Berlev [a], K.V. Gusak [g], I.V. Kudashkin [a],
J. Khushvaktov [a], M. Paraipan [a,d], V.S. Pronskikh [a,i,*], A.A. Solnyshkin [a], V. Sotnikov [f],
V.I. Stegaylov [a], S.I. Tyutyunikov [a], V. Voronko [f], M. Zeman [a,e], I. Zhuk [g]

[a] *Joint Institute for Nuclear Research, Dubna, Russia*
[b] *Nuclear Physics Institute ASCR, Czech Republic*
[c] *Institute for Advanced Studies "OMEGA", Dubna, Russia*
[d] *Institute of Space Science, Bucharest-Magurele, Romania*
[e] *Faculty of Electrical Engineering and Communication Brno University of Technology, Brno, Czech Republic*
[f] *NSC Kharkov Institute of Physics and Technology, Kharkov, Ukraine*
[g] *Joint Institute for Power and Nuclear Research-Sosny near Minsk, Belarus*
[h] *Moldova Academy of Sciences, Kishinev, Republic of Moldova*
[i] *Fermi National Accelerator Laboratory, Batavia, USA*

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ABSTRACT

The spatial distribution of particle fluences in the extended uranium target ("Quinta" assembly) irradiated by 0.66 GeV proton, 4 AGeV deuteron and carbon beams is studied by analyzing the accumulation rates of the isotopes with different threshold energy (E_{th}) in ^{59}Co samples. The accumulation rates for the following isotopes: ^{60}Co ($E_{th}\approx 0$ MeV), ^{59}Fe ($E_{th}\approx 3$ MeV), ^{58}Co ($E_{th}\approx 10$ MeV), ^{57}Co ($E_{th}\approx 20$ MeV), ^{56}Co ($E_{th}\approx 32$ MeV), ^{47}Sc ($E_{th}\approx 55$ MeV) , and ^{48}V ($E_{th}\approx 70$ MeV) were measured using the HPGe spectrometer. The experimental accumulation rates and the reconstructed neutron spectra are compared with the simulations using the codes Geant4 and MARS15. The noticeable difference between the simulated and the experimental data, especially in the hard part of the neutron spectrum, is analyzed.

1. Introduction

The use of proton accelerators in reactor technology has been extensively investigated [1–4]. A high intensity spallation source obtained by irradiating a heavy target with an accelerated beam may provide the functioning of a deeply sub-critical reactor and the possibility to burn minor actinides and to recycle them until they fission completely. The classical concept of an energy amplifier, developed in [3] involves the use of proton beams with energies around 1 GeV and a heavy metal target (tungsten, lead, uranium) surrounded by a subcritical core. Measurements of fission products and temperature distribution in an extended uranium target irradiated by protons with energies between 600 MeV and 2.75 GeV (FEAT experiment [4]) show a certain energy gain for proton energy above 1 GeV. A similar result was obtained at JINR, Dubna (E&T collaboration) using fission products distribution in natural uranium target irradiated by deuteron beams with energies from 0.5 to 4 AGeV [5,6].

The possibility to use heavy ion beams for ADS was analyzed in [7]. Simulations performed using the code Geant4 in a quasi-infinite uranium target predict that one cannot improve the energetic efficiency of proton or deuteron beams by increasing the beam energy above 2–3 AGeV, but one can get a higher efficiency by accelerating heavier ions [8]. Based on this fact, a series of experiments with ion beams started at JINR. A more detailed analysis of particle distributions and spectra was realized by measuring the accumulation rates of isotopes with threshold energies from 0 to 70 MeV, using probes of ^{59}Co placed at different positions inside the target. In this study the distribution of the accumulation rates of these isotopes in the uranium target "Quinta" irradiated by 0.66 GeV proton, 4 AGeV deuteron and carbon beams is presented. The experimental data are compared with the predictions obtained using Geant4 [9].

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[*] Corresponding author at: Fermi National Accelerator Laboratory, Batavia, USA
E-mail address: vspron@fnal.gov (V.S. Pronskikh).

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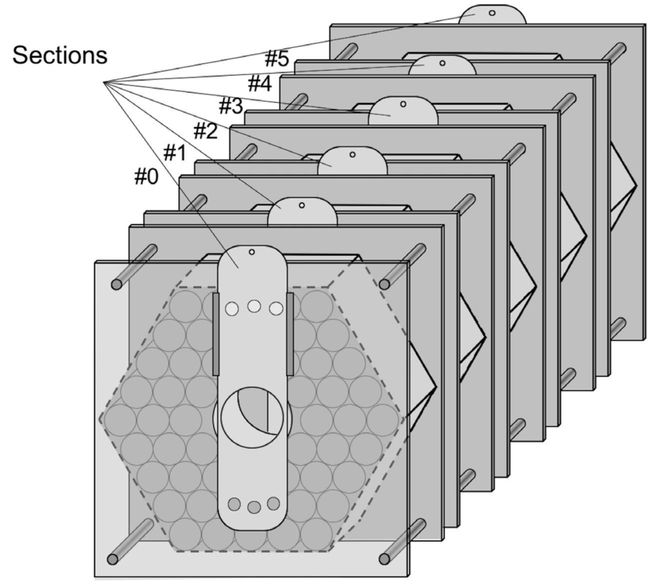

Fig. 1. The schematic diagram of the "Quinta" assembly.

2. Experimental setup

The "Quinta" assembly was already described in detail in [10,11]. Here we give a brief outline of this target. The target consists of five uranium sections, with 17 mm gaps between them, allowing the mounting of detectors. Each section is an assembly of uranium rods with a diameter of 36 mm and a length of 104 mm, placed in a hexagonal aluminum container. The first section has a beam window with a diameter of 80 mm in order to reduce the neutron leakage. The total uranium mass is ~512 kg. The entire assembly is surrounded by a 10 cm thick lead blanket. The schematic diagram of the target is shown in Fig. 1.

The samples are mounted on aluminum plates at different distances from the center. The plates are inserted into the spaces between the sections. The choice of Co as the sample material was determined by certain advantages that it presents. One advantage is the fact that the material is mono-isotopic (^{59}Co). Another advantage is the existence of sufficient experimental data on the excitation function under irradiation by neutrons and protons for the following isotopes covering a wide neutron energy range: ^{60}Co (threshold energy $E_{\rm th} \approx 0$ MeV), ^{59}Fe ($E_{\rm th} \approx 3$ MeV), ^{58}Co ($E_{\rm th} \approx 10$ MeV), ^{57}Co ($E_{\rm th} \approx 15$ MeV), ^{56}Co ($E_{\rm th} \approx 25$ MeV), ^{47}Sc ($E_{\rm th} \approx 55$ MeV), and ^{48}V ($E_{\rm th} \approx 70$ MeV). Available experimental data on an isotope cross section is an important condition for using the isotope for the comparison with the simulated spectra and for the reconstruction of the energy spectrum of the particles. For neutrons the experimental data on the excitation functions in Co are available for energies until 180 MeV. For higher energies we use the values obtained with Geant4 and the binary cascade model (which provides the predictions closest to the experimental data for both protons and neutrons) properly adjusted to agree with the experimental data. The excitation functions for neutrons and protons in cobalt are presented in Fig. 2(a) and (b). An example of the simulated neutron spectrum registered at a longitudinal position of 39 cm and a radius of 8 cm is shown in Fig. 2(c). This figure also shows the threshold energy for the isotopes. The probabilities of isotope production for to the spectrum in Fig. 2(c) are shown in Fig. 2(d), as functions of the neutron energy. This figure illustrates the energy interval in which the accumulation rate of a given isotope provides maximum information on the neutron fluence. The neutron energy intervals corresponding to the 90% confidence intervals of accumulation rate for given isotopes are: 3–40 MeV for ^{59}Fe, 10–40 MeV for ^{58}Co, 20–200 MeV for ^{57}Co, 30–300 MeV for ^{56}Co, >60 MeV for ^{47}Sc, and >80 MeV for ^{48}V.

The target was irradiated by protons with an energy of 0.66 GeV, deuteron and carbon beams with an energy of 4 AGeV. The beam position was monitored using the multiwire and pad ionization chambers. Solid state track detectors placed on the front side of the target were also used. The total beam intensity was measured with ionization chambers (for deuteron and carbon beams) and by activation of Al foil for the proton beam (reaction $^{27}\mathrm{Al(p,x)}^{24}\mathrm{Na}$). Detailed description of the beam monitoring system can be found in [12]. The values of the integral beam intensity (irradiation time) were $2.5 \cdot 10^{15}$ (5 h) for 0.66 GeV protons, $6.2{\cdot}10^{12}$ (10 h) for 4 AGeV deuteron beam, and $4.8{\cdot}10^{10}$ (10 h) for 4 AGeV carbon beam, measured with a relative error of 10%. The accumulation rates of the isotopes in each sample were determined by measuring the γ-activities using the HPGe γ-spectrometers. The spectrometers were calibrated with a set of standard γ-sources. The reported error for the activity of γ-standards is 2%.

3. Experimental results

The experimental values for the accumulation rate of the isotopes measured under irradiation by 0.66 GeV protons are given in Table 1. The absolute errors given in the table include the contributions from uncertainties of γ-activity and beam intensity measurements. In the first column of the table the longitudinal (z, beam direction) and radial (r) positions of the sample are given. The radial position is given with respect to the beam axis, it was calculated taking into account the position of the beam center with respect to the center of the plate at each section. In a similar manner, the accumulation rates of isotopes for the target irradiated by a deuteron beam with an energy of 4 AGeV are given in Table 2.

The spatial distribution of accumulated isotopes depends on the projectile type, initial energy and the threshold energy for the isotopes.

The comparison between the radial distribution of ^{59}Fe, ^{58}Co and ^{48}V in the case of irradiation by 0.66 GeV protons and 4 AGeV deuterons is shown in Fig. 3. The accumulation rates of the isotopes $N_{\rm isot}$ are plotted as functions of radius, for z = 39 cm (after the second section, Fig. 3(a)) and $z = 78$ cm (after the fifth section, Fig. 3(b)). The data are scaled by the factors shown in the figure, in order to present all three isotopes in the same figure.

The distribution of an isotope reflects the distribution of particles with the energy above the isotope threshold energy. The distributions can be well parameterized with one (for ^{60}Co, ^{59}Fe) or two exponentials (for the isotopes with higher energy threshold). The corresponding fits are shown in Fig. 3(a) and (b). Due to the fit simplicity, we choose it to present the distributions for calculating the values of isotopes at a given distance from the beam axis. The distributions represented in this way reflect the presence of the material, as well as the influence of the geometric factor on the particle fluence. For a point source the geometric factor implies the fluence decrease as $1/r^2$. The approximation of the beam as a linear source yields the geometric factor of the form $1/r$ (r is the distance from the beam line). If we eliminate the influence of the geometry by representing the distributions in the form $r \cdot N_{\rm isot}$ as functions of the radius r, we get a better understanding of the development of the nuclear cascade and particle fluences inside the target. Such representation is shown in Fig. 4 for the isotopes ^{60}Co, ^{58}Co, and ^{56} Coregistered after the fourth section ($z = 65$ cm). The distribution of ^{60}Co demonstrates that the fluence of neutrons with the energy below 10 MeV is still in the build-up zone for both 0.66 GeV protons and 4 AGeV deuteron beams. For isotopes with higher energy threshold the distributions are sufficiently different. In the case of irradiation by 0.66 GeV protons the fluences pass through the build-up zone and start to decrease exponentially. In the case of irradiation by 4 AGeV deuteron beam the region of exponential decrease is not reached. This observation leads to an important conclusion. For correct comparison of integral quantities, such as energy deposition and the number of fissions,