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Monte-Carlo study of induced radioactivity in probe for low-energy proton beam

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ABSTRACT

Induced radionuclides generated from the probe which is bombarded by proton beam will turn the detector into a typical external irradiation radiation source. Thus, it is beneficial for developing radiation protection to calculate the types and the activities of radionuclides. Here we applied both a theoretical analysis and a Monte-Carlo method to compute the induced radioactivity in a copper probe irradiated by proton beam. Various kinds of radionuclides saturation activity obtained by these two different methods were compared. The comparisons of the results cast by the two methods show the similar saturation activities for ^{63}Zn and ^{65}Zn. However, the Monte-Carlo method conducted by the software FLUKA is able to provide a more complete consideration on nuclear reaction, and to calculate both the direct and indirect radioactivity under different irradiation time. Furthermore, by employing the FLUKA Monte-Carlo program, the induced radioactivity of three types of probe materials (Cu, Ta and W) under low-energy (below 20 MeV) proton beam irradiated were also separately simulated and tantalum is considered as the best material for low-energy proton interceptive diagnostics probe due to the higher energy threshold of nuclear reaction and the lower radioactivity.

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1. Introduction

The low-energy cyclotron (below 20 MeV) has been widely used in the fields of nuclear medicine and nuclear physics basic research, especially in the isotope production, radioactivity isotopes produced via nuclear fragmentation reactions between the monoenergetic proton beams in the energy and intensity range and the target nuclei [1]. To obtain the minimum of energy spread and the maximum of beam intensity in the on-line debugging of cyclotron, it is extremely important to measure beam parameters. Generally the beam deposition method is used to measure the beam depositing on a probe [2–4]. The nuclear reaction occurs when the high-energy protons produced in an accelerator bombard the atomic nucleus of probe material, and a new atomic nucleus called recoiled nucleus will be produced in the probe. These recoiled nuclei are always unstable, and will evolve to stable nuclei via β or γ decay. This is called induced radioactivity with some new radionuclides produced.

The physics principle of induced radioactivity in proton cyclotron should be divided into direct and indirect processes. The direct process is a nuclear reaction happened between proton and material. Below 20 MeV, this direct process is mainly the single charge exchange reaction (p, n), which produces neutrons and radionuclides. Those nuclides are normally neutron-deficient short-lived nuclides with β^+ decay. The indirect process is neutron activation (n, γ), which happens when neutrons produced in direct process are captured by nuclei. Those new nuclides are always neutron-rich nuclides with β^- decay or orbital electron capture. The induced radioactivity can be ignored when the beam energy is below 5 MeV, while the radionuclides will be generated in probe when the beam energy is higher [5,6]. Therefore, we should focus our attention on the types and the activities of radionuclides in probe, mainly trying to understand the activity of radionuclides under a certain irradiation time and dose level of the cooling time. Knowing those results analysis should have a better basis for choosing the best material for probe and provide us references for replacement and post-treatment probe.

We organize the paper as follows. Section 2 describes the induced radioactivity and various kinds of radionuclides saturation activity in a copper probe irradiated by proton beam with both theoretical analysis and Monte-Carlo method simulation. By employing FLUKA Monte-Carlo program, the induced radioactivity of three types of probe material (Cu, Ta and W) are separately simulated under low-energy (below 20 MeV) proton beam irradiated in Section 3. Finally, Section 4 discusses the preliminary conclusions on choosing the best probe material, and gives an outlook on the future experimental investigations planned in induced radioactivity.

2. The comparison of induced radioactivity in theoretical analysis and Monte-Carlo method simulation

The strength of induced radioactivity is generally described by saturation activity (As) [7], which is activity in the moment of

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cutting off the accelerator after running a long cycle stably. Long-period is relative to nuclear half-life, in fact, 4–5 times of half-life can be assumed to approximate. As is numerically equal to the number of radionuclides produced in unit time, and its unit is Becqurel (Bq).

Calculation conditions:		
Proton energy	11 MeV	Average intensity 50 μA
Probe material	Copper (^{63}Cu, 69%; ^{65}Cu, 31%)	Density 8.96 g/cm^3
Probe thickness	2 mm	

2.1. Theoretical analysis

The theoretical computation of induced radioactivity has been discussed completely elsewhere [8–10] and will be summarized here. The traditional calculation method of As is based on the principles of nuclear reaction, but it applies only to direct nuclear reaction. The As of isotope productions are calculated from incident particle intensity, available spallation cross-sections, and energy loss per unit path length. Considering the probe thickness is larger than the particle range, the probability of nuclear reaction is given by

$$P = N_v \int_0^D \sigma(E)dx \approx N_\nu \int_0^{E_0} \left[\sigma(E) \Big/ \left(-\frac{dE}{dx}\right)\right] dE \quad (1)$$

where P is the probability of nuclear reaction, N_v is the number of target nucleus in unit volume, D is the particle range, E_0 is the initial energy, $\sigma(E)$ is the cross-sections when the proton energy is E, and $-dE/dx$ is the energy loss per unit path length.

If the intensity of incident particle is I and the irradiation time is t, the radioactive decay of a new nuclide should satisfy the following formula

$$N = \frac{PI}{\lambda e}(1 - e^{-\lambda t})e^{-\lambda t'} \quad (2)$$

where t' is the cooling time and λ is the decay constant of the new nuclide.

At the moment, the corresponding instant radioactive activity is

$$A = \left.\frac{dN}{dt'}\right|_{t'=0} = \frac{PI}{e}(1 - e^{-\lambda t}) \quad (3)$$

If the irradiation time $t_{\to\infty}$ the formula for saturation activity could be rewrite as

$$A_s = \lim_{t\to\infty} A = \lim_{t\to\infty}\left(\left.\frac{dN}{dt'}\right|_{t'=0}\right) = \frac{PI}{e} \quad (4)$$

The interaction of 11 MeV protons with copper probe is simulated using the software SRIM [11,12] (Monte-Carlo simulation). The average range of protons is 0.3 mm, and 99.95% of protons are ionization energy loss in the probe. $-dE/dx$ as simulated by SRIM is shown in Fig. 1.

Considering the direct reactions of protons with copper, they are only ^{63}Cu (p, n) ^{63}Zn and ^{65}Cu (p, n) ^{65}Zn due to low energy of proton (below 11 MeV). The nuclear reactions cross-sections for ^{63}Cu (p, n) ^{63}Zn and ^{65}Cu (p, n) ^{65}Zn in different proton energy can be searched [13].

Discretizing (1), we obtain

$$P = N_v \int_0^{E_0} \left[\frac{\sigma(E)}{-\left(\frac{dE}{dx}\right)}\right] dE = N_v \left(\frac{\Sigma_{E_{min}}^{E_{max}} \sigma(E_i)}{\left(-\frac{dE}{dx}\right)_i}\right) \Delta E \quad (5)$$

Take the energy loss per unit path length and the nuclear reaction cross-sections into the formula (5), and considering natural cooper content of about 69.1% ^{63}Cu

$$N_v = N_A \frac{\rho}{M} \times 69.1\% \quad (6)$$

We can get the probability of nuclear reaction ^{63}Cu (p, n) ^{63}Zn

$$P = 2.86 \times 10^{-4}$$

Finally, the saturation activity of ^{63}Zn by formula (4) that is, $A_s = 8.9 \times 10^{10}$ Bq in the irradiation of 50 μA proton beam could be obtained.

Similarly, considering natural cooper content of about 30.1% ^{65}Cu, we can get the saturation activity of ^{65}Zn which is $A_s = 1.3 \times 10^{11}$ Bq.

2.2. Simulation

Based on the basic principles of Monte-Carlo method, the software FLUKA [14,15] can be used to simulate induced radioactivity [16,17]. The code has been successfully employed for calculating induced radioactivity at both proton and ion accelerators

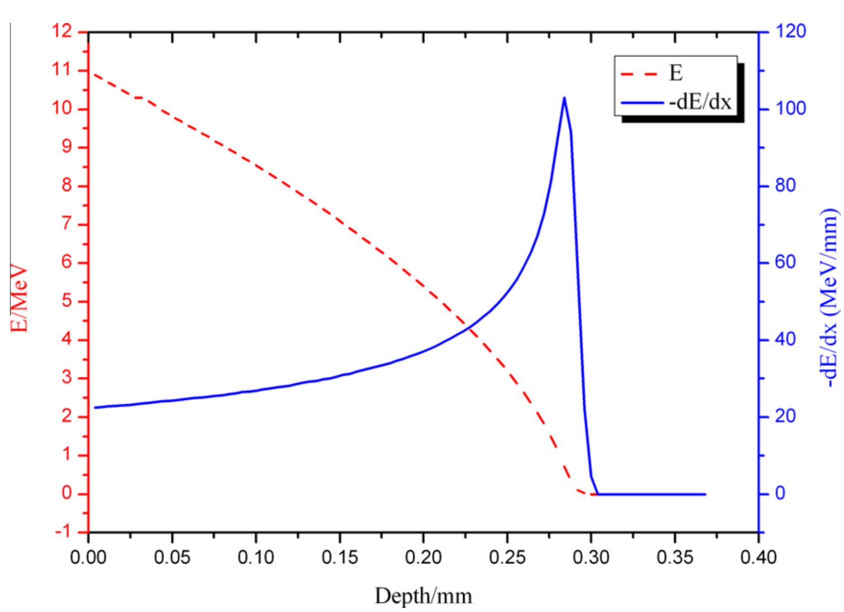

Fig. 1. Dependence of proton beam energy and energy loss per unit path length on the copper target depth (SRIM simulation).

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