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Annals of Nuclear Energy 33 (2006) 786–793

annals of NUCLEAR ENERGY

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Investigation of $^{203}_{81}Tl(p,3n)^{201}_{82}Pb$ nuclear reaction in a cyclotron accelerator as a neutron source

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Received 12 February 2006; received in revised form 11 April 2006; accepted 1 May 2006
Available online 22 June 2006

Abstract

Using cyclotron accelerator (at Cyclotron Dept. in Karaj) the radioisotope ^{201}Tl is produced through the $^{201}_{81}Tl(p,3n)^{201}_{82}Pb \xrightarrow{Ec,\beta^+} {}^{201}_{81}Tl$ reaction.

The main objective of this paper is to calculate the intensity, energy spectrum and angular distribution of the neutrons produced from the above reactions. The reason is that, if the neutron characteristics are reasonable enough then at the same time that ^{201}Pb (and subsequently ^{201}Tl) is produced, the above nuclear reaction can be considered as a neutron source, which in turn can be applied for different purposes. Of course depends on the application, the neutrons must be collimated and thermalized (if thermal neutron is needed for example for neutron activation analysis). Besides, the knowledge about the characteristics of the emitted neutrons can help us to predict the activity of the concrete walls and equipments in the target room. And also it is possible to design shielding for these sorts of neutron sources.

In this paper the intensity, energy spectrum and angular distribution of neutrons produced from the above mentioned reaction is investigated. In our investigation the thickness of thallium layer assumed to be 70 μm coated on copper sub-layer. The target (thallium) was bombarded by protons with energy 28.5 MeV and 200 μA current. By using the computational code SRIM2000 the average proton energy at different points of the traveling path was calculated and then by using computational code ALICE91 and reaction rate equation, the neutron intensity from the $^{203}_{81}Tl(p,3n)^{201}_{82}Pb$ reaction was determined to be 1.26×10^{13} n/s.

With the same method, the neutron intensity produced from the copper sub-layer i.e. from $^{63}Cu + p \rightarrow {}^{63}Zn + n$ nuclear reaction was calculated to be 9.19×10^{12} n/s. As a result, the total neutron intensity from thallium target and its copper sublayer was determined to be 2.179×10^{13} n/s, which is comparable with some conventional neutron sources such as Am–Be neutron source, and is high enough to be applied for different purposes. Our calculations also showed that the neutron energy spectrum from thallium target and its copper sublayer has a peak around 1 MeV region. The angular distribution of produced neutrons, has its maximum value at angle 0–2.5° and decreases slowly as the angle of neutron emission increases, and its minimum value occurs at backward direction, i.e. 177.5–180°. It means that the produced neutrons, are mostly emitted in the forward direction.

1. Introduction

Using cyclotron accelerator (at Cyclotron Dept. at NRCAM) the radioisotope ^{201}Tl (for radiopharmaceutical ^{201}Tl) is produced through the following nuclear reaction (Qaim, 1979; Shuvin, 2001):

$$^{201}_{81}Tl(p,3n)^{201}_{82}Pb \xrightarrow{Ec,\beta^+} {}^{201}_{81}Tl$$

The above nuclear reaction is used routinely to produce radioisotope ^{201}Tl which then is used for ^{201}Tl radiopharmaceutical. In addition to radioisotope ^{201}Tl, three neutrons are also emitted. Beside that, the reaction of

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doi:10.1016/j.anucene.2006.05.002

protons (bombarding particles) with the copper sub-layer (for thallium layer) results in producing a neutron through the following reaction:

$$^{63}\mathrm{Cu} + \mathrm{p} \rightarrow {}^{63}\mathrm{Zn} + \mathrm{n}$$

The main objective of this paper is to calculate the intensity, energy spectrum and angular distribution of the neutrons produced from the above reactions. The reason is that, if the neutron characteristics are reasonable enough then at the same time that ^{201}Pb (and subsequently ^{201}Tl), is produced the above nuclear reactions can be considered as a neutron source, which in turn can be applied for different purposes. Of course depends on the application, the neutrons must be collimated and thermalized (if thermal neutron is needed for example for neutron activation analysis). Besides, the knowledge about the characteristics of the emitted neutrons can help us to predict the activity of the concrete walls and equipments in the target room. And also it is possible to design shielding for these sorts of neutron sources.

In doing so, it is necessary to determine the above reaction rates which are strongly depends on the bombarding proton energy and consequently the reaction cross section. The initial bombarding proton energy is 28.5 MeV but it decreases as it penetrates the thallium target and copper sub-layer. The mean proton energy at different points of proton's path in the target and sub-layer is determined by using the computational code SRIM2000 (Biersack and Ziegler, 2000). Having these values, the computational code ALICE91 (Blann, 1991; Salehi, 1993) is used to determine the energy dependent reaction cross sections. Then using the equation $\mathrm{RR} = \Phi(E) \cdot N \cdot \sigma(E)$ the reaction rates, RR (s^{-1}), and finally the neutron intensity will be calculated. In this equation, Φ(E) is the incident proton flux (particles/s cm^2) with energy E, N is the number of target nuclei and $\sigma(E)$ is the energy dependent reaction cross section (cm^2). In addition to the main (p, 3n) reaction, other types of reactions such as (p, n) and (p, 2n) will also occur during thallium bombardment which results in producing neutrons. Therefore in our investigation the neutron produced from the two last reactions are also considered.

In addition to reaction cross sections, the computational code ALICE91 gives the angular distribution and energy spectrum of the emitted neutrons.

2. Method of calculation

In producing radioisotope ^{201}Tl (for radiopharmaceutical ^{201}Tl) through the nuclear reaction

$$^{203}\mathrm{Tl}(\mathrm{p}, 3\mathrm{n})^{201}_{82}\mathrm{Pb} \overset{\mathrm{Ec},\beta^+}{\rightarrow} {}^{201}_{81}\mathrm{Tl} \tag{1}$$

the thallium target with 70 μm thickness and area 10 cm^2 (with a mass nearly 1 g) is bombarded by proton particles with energy 28.5 MeV and 200 μA current produced by cyclotron accelerator CYCLON30.

The angle between the incident proton particles and horizontal target surface is 6°, that it means the traveling path of protons through the thallium target is about 700 μm.

As a charged particle, the energy of incident proton decreases as it travels through the target. The decrement of energy per unit path, shown by dE/dx and called " stopping power" is calculated by computational code SRIM2000. To do so, the traveling path of proton was divided to several segments, each with a length of 20 μm. By applying the computational code SRIM2000 to the first segment (with the input energy 28.5 MeV) the stopping power in keV/μm was obtained. If the length of the first segment assumed to be ΔX, therefore, the proton energy decrement in the first segment was calculated using the following equation:

$$\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{E_i} \times \Delta X = \Delta E \tag{2}$$

Therefore, the energy of proton leaving the first segment, will be :

$$E_2 = E_1 - \Delta E \tag{3}$$

and the average energy of proton in the first segment will be simply $E_{\mathrm{ave}} = \frac{E_1+E_2}{2}$. The average energy of the incident particles as an input data for computational code ALICE91 is used to calculate the reaction cross section in Eq. (1).

As the proton emerges from the first segment , it enters the second segment with the energy E_2. With the same method applied for the segment 1, the average energy of the proton in the second segment can be calculated. And by using the computational code ALICE91 the nuclear reaction cross-section in the second segment is determined. This method is applied to the all thallium segments and the average proton energy and consequently the nuclear reaction cross-section in different points of the proton path is determined. In our calculation it is assumed that:

atomic mass of proton = 1.008 amu
incident (initial) proton energy = 28.5 MeV
thallium mass density = 11.85 g/cm^3
thallium atomic mass = 203.06 amu (^{203}Tl enrichment is %97)

The results of the calculations for the 700 μm traveling path of proton in the target (divided into 35 segments) is shown in Table 1 and the proton energy decrement is shown in Fig. 1. The stopping power as a function of proton energy in thallium target is shown in Fig. 2.

As it is seen from the Table 1, the energy of proton emerging the last thallium segment is 20.51 MeV. The proton with this energy then entering the copper sub-layer and eventually is stopped in this sub-layer. With the same method mentioned for the thallium layer, the copper sub-layer was also divided into several segments each with a length of 50 μm. The number of the segments for the sub-layer was chosen such that the energy of proton