Radiation shielding design requirement in the proton energy measurement facility at DECY-13 cyclotron

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Abstract. The DECY-13 cyclotron is expected to produce a maximum energy of protons beam of 13 MeV. For testing the proton energy, a device for measuring photon energy using a stacked copper foil activation technique is currently being constructed. The activation caused the collision of a proton with copper foils and reactions of \( ^{63}\text{Cu}(p,n)^{63}\text{Zn} \) and \( ^{65}\text{Cu}(p,n)^{65}\text{Zn} \) have happened. These nuclear reactions produce neutron and gamma radiations; therefore, a study of radiation safety aspects is required to protect the hazard in the experiment of proton energy measurement. The study consists of designing for shielding construction based on radiation safety criteria and mainly determining the thickness of the shielding. The shielding material was portland cement concrete of K500 with a density of 2.3 gr/cm\(^3\). By setting a safe maximum dose rate of 50 mSv/year in the position of 350 cm from the neutron radiation source and the proton beam current was taken 1 \( \mu \)A, the required minimum thickness of concrete shielding was 110 cm.

1. Introduction

The commissioning process of a cyclotron accelerator for the production of radioisotopes is carried out by diagnosing the output of cyclotron that is ion beam current and ion beam energy. The DECY-13 cyclotron accelerates the negative H ions beam, which after reaching maximum energy (and maximum radius), will be converted into a proton beam through a stripping process on a carbon foil. Measuring the energy of a negative hydrogen beam in the maximum energy is done by measuring the energy of the proton extracted from the stripper.

The measurements of proton beam energy were carried out by a stacked foil activation method, as carried out by Kim et al. [1]. The proton beam of around 13 MeV energy that bombards the copper foils produces radiation exposure, which mainly comes from the \( ^{63}\text{Cu}(p,n)^{63}\text{Zn} \) and the \( ^{65}\text{Cu}(p,n)^{65}\text{Zn} \) reactions [2,3]. Both reactions produce a neutron and gamma radiation, so the safety aspects of nuclear radiation need to be taken into account. The neutron radiation comes directly from nuclear reactions and gamma-ray radiation comes from the decay of \(^{63}\text{Zn} \) and \(^ {65}\text{Zn} \).

Compared to neutron yield, the gamma yield only differs with the factor of \((1-e^{-\lambda t})\) where \( \lambda \) is constant decay of \(^{63}\text{Zn} \) or \(^{65}\text{Zn} \), and \( t \) is activation time. Considering the decay constant of \(^{63}\text{Zn} =3.0 \times 10^{-4} /s \) and \(^{65}\text{Zn} = 3.3 \times 10^{-8} /s \), that is the constant decay of \(^{63}\text{Zn} \) much bigger than constant decay of \(^{63}\text{Zn} \), and it means enough if calculating the yield of \(^{63}\text{Zn} \) only when calculating gamma yield. By taking activation time \( t=10 \text{ min} (=600 \text{ s}) \) and constant decay of \(^{65}\text{Zn} \), the factor of \((1-e^{-\lambda t}) = 0.165 \). By considering the value of this factor, it can be concluded that the contribution of gamma yield gives a small contribution to the radiation aspect compared to neutron yield.
For occupational exposure of workers over the age of 18 years, the maximum dose is 50 mSv in any single year [4]. If it is assumed, there are 2000 working hours in a year, and then the maximum dose rate is equivalent to 25 µSv/hour; therefore, a shielding with sufficient thickness is required for making the dose rate below the safe exposure limit. The experiment of proton beam energy measurement will be done for 10 minutes and for only done once namely during the commissioning of the cyclotron.

In this paper, the calculation of shielding thickness for safe maximum radiation exposure using portland cement concrete (K500, the density of 2.3 gr/cm³) will be discussed. Concrete has been used as shielding for high-energy photons and neutrons because the concrete has been used since at the beginning of the usage of nuclear reactions in energy, medicine and research [5]. Furthermore, civil or mechanical construction was will be also discussed.

2. Methodology

2.1. The layout of the Proton Energy Measurement Facility

The proton energy measurement in DECY-13 Cyclotron consists of a stacked foil of Cu in the chamber (or the target chamber) of the aluminum tube. The inner diameter of the chamber is 8 cm and the length is 20 cm. In the surrounding of the chamber, there are blocks of concrete as shielding of radiation. The average thickness of the total blocks is \( t \) cm, which needs to be calculated. The layout of the measurement facility is shown in Figure 1.

![Figure 1. The layout of cyclotron with proton energy measurement facility (top view)](image)

2.2. Fixed Parameters. The study was conducted by analyzing and determining the thickness of the shielding that met the radiation safety requirements at a point of 3.5 m from the neutron source, which occurred due to proton beam collision with a stack of copper foils. The fixed parameters were specified as follows:

1. The material of shielding is was cement portland concrete K500 with a mass density of 2.3 gr / cm³
2. The proton beam current that activated a stack of copper foils was 1 µA
3. At a distance of 3.5 m or 350 cm from the neutron source point, the maximum neutron exposure dose that is safe for radiation workers was in the value of 25 µSv/hour.
2.3. **The procedure of Design Calculation.** Determination of the thickness of the shielding through the steps as follows: First, the maximum neutron flux at 350 cm position was set and followed by the calculation of maximum neutron flux on the outer edge of the shielding. The second step was calculating the neutron yield on the activation chamber (or target chamber) and followed by the calculation of the neutron flux on the outside of the chamber or the inner edge of the shielding. The results of the first and second steps were then used to determine the shielding thickness that allows the maximum neutron flux to occur at the outer edge of the shielding on the basis of the neutron flux generated at the inner edge of the shielding.

2.3.1. **The maximum neutron flux.** The maximum neutron flux was based on the provisions of the maximum safe dose rate for radiation workers that was equal to 25 µSv/hour. The conversion of the neutron radiation exposure dose rate from the flux value $\phi$ is

$$\dot{H} = 3.6 \times 10^3 \frac{\phi}{F}$$  \hspace{1cm} (1)

where $\dot{H}$ is the exposure dose rate in the unit of rem/hr, $F$ is the factor that shows the equality value of neutron fluent in a unit of n/s with a dose in units of n/cm$^2$/rem. The number of $3.6 \times 10^3$ (in the unit of s/hour) is the conversion value of the number in the unit of n/cm$^2$/s to n/cm$^2$/hr. The $F$ value based on the US Nuclear Regulatory Commission for 2 MeV fast neutrons is equal to be $29 \times 10^6$ n/cm$^2$/rem [$6]$. Because 1 rem = 10$^4$ µSv, the $F$ value is equal to be $29 \times 10^2$ n/cm$^2$/µSv, and then equation (1) becomes

$$\dot{H} = 1.2 \times \phi$$  \hspace{1cm} (2)

wherein the unit of µSv/hr and $\phi$ in the unit of n/cm$^2$/s.

2.3.2. **Calculation of maximum neutron flux in the outer edge of the shielding.** The neutron source coming from the activation of the copper proton beam and for simplification is considered as a neutron point source that radiates in all directions with even distribution. Because the neutron source has a chamber, therefore the neutron flux $\phi_0$ outside the cylindrical chamber with a thickness of $d$ cm from the neutron source point with a yield of $Y$ was

$$\phi_0 = \frac{Y}{4\pi d^2}$$  \hspace{1cm} (3)

In this calculation, it was considered that there was no reduction in neutron flux due to neutron absorption by the target chamber material.

2.3.3 **Determination of neutron yield.** To determine the exposure strength of neutrons to be shielded, firstly, the yield neutrons produced in the target material for energy measurement were calculated. The target material was natural copper, whose composition consisted of 69% of $^{63}$Cu and 31% of $^{65}$Cu.

The neutron yield of the $^{63}$Cu(p,n)$^{63}$Zn and $^{65}$Cu(p,n)$^{65}$Zn reactions was calculated by using a formulation of [7,8]:

$$Y = \frac{6.25 \times 10^{25} N_A}{Z} \left( \sum \frac{E_{th}}{E_i} \frac{\sigma(E)}{E} \Delta E \right) \text{ n/s}$$  \hspace{1cm} (4)

where $I$ proton beam current (as a free variable) in unit of ampere, $Z$ charge number of proton that is 1, $N_A$ Avogadro number is $6 \times 10^{23}$ atom per mol, $\rho$ mass density of Cu is 8.96 g/cm$^3$ [9], $M$ atomic mass of Cu is 63,546 g/mol [9], $E_{th}$ reaction threshold energy for $^{63}$Cu(p,n)$^{63}$Zn is 4 MeV, and for $^{65}$Cu(p,n)$^{65}$Zn is 3 MeV [10], $E$ incident photon energy is 13 MeV, $\sigma(E)$ nuclear reaction cross-section at the energy $E$ in cm$^2$ which can be created from EXFOR [11] (shown in Table 1 and 2),
\( \left( \frac{1}{p} \frac{dE}{dx} \right) \) is stopping power of proton on Cu in MeV cm\(^2\)/gr, which can be created by PSTAR program [12] (shown in Table 3), and \( \Delta E \) is step energy of incident proton that is taken = 0,5 MeV. If \( I \) am taken in ampere, \( Y \) will be expressed in neutrons per second.

By entering Avogadro \( N_A \) number, \( M \) for copper and \( Z \) for protons = 1, equation (1) becomes

\[
Y = 5.9 \times 10^{40} \times I \left( \frac{\sum E_{th}}{p \frac{dE}{dx}} \right) \frac{\sigma(E)}{\Delta E} \text{ n/s} \quad (5)
\]

where \( I \) in ampere, \( \sigma(E) \) in cm\(^2\), \( \Delta E \) in MeV and \( (1/\rho \frac{dE}{dx}) \) in MeV cm\(^2\)/g. Then because Cu consists of 69% of \(^{63}\)Cu isotope and 31% of \(^{65}\)Cu isotope, equation (5) can be changed to be

\[
Y_{63} = 5.9 \times 10^{40} \times I \times 0.69 \left( \frac{\sum E_{th}}{p \frac{dE}{dx}} \right) \frac{\sigma(E)}{\Delta E} \quad (6)
\]

and

\[
Y_{65} = 5.9 \times 10^{40} \times I \times 0.31 \left( \frac{\sum E_{th}}{p \frac{dE}{dx}} \right) \frac{\sigma(E)}{\Delta E} \quad (7)
\]

where the values of \( E_{th} \) and \( \sigma(E) \) differ each other for the two isotopes. The total yield value is the sum of \( Y_{63} \) and \( Y_{65} \).

2.3.4. Neutron flux calculation in the outer edge of the target chamber. For simplification, the neutron source coming from the activation copper foils by a proton beam is considered as a point neutron source that radiating neutron in all directions with even distribution. The foils are contained in a cylindrical chamber has a thickness \( d \) cm. If the total activation yield is \( Y \), the neutron flux \( \phi_0 \) outside the cylindrical chamber is

\[
\phi_0 = \frac{Y}{4\pi d^2} \quad (8)
\]

In this calculation, it is assumed that there is no reduction of neutron flux due to neutrons absorption by the chamber material.

2.3.5. The shielding calculation. To determine the neutron radiation exposure that was safe for radiation workers, the shielding thickness was calculated by calculating the neutron flux attenuation using the equation

\[
\phi_t = \phi_0 e^{-\Sigma_R t} \quad (9)
\]

where \( \phi_t \) was a neutron flux with shielding as thick as \( t \), \( \phi_0 \) was a flux without a shielding, \( t \) was the shielding thickness (in cm), \( \Sigma_R \) was the neutron absorption latitude in the shielding (in cm\(^{-1}\)). The \( \Sigma_R \) value was related to the TVL value, which is the shielding thickness value where the radiation dose rate has decreased by one-tenth of the initial dose rate, and its relationship is expressed in [13]:

\[
\Sigma_R = \frac{\ln 10}{TVL} = \frac{2.3}{TVL} \quad (10)
\]

3. Result and Discussion

3.1. Maximum Neutron Flux on the Outer Edge of the Shielding

From equation (2), it could be easily calculated that the neutron flux to produce a maximum dose rate of 25 \( \mu \)Sv was 20.8 n/cm\(^2\)/detik. This was the maximum flux value expected to occur at a distance of 350 cm from the neutron source. Furthermore, the calculation of the maximum neutron flux on the
outer edge of the shielding at a distance of \( t \) cm from the neutron source was used equation (3) that was with the proportional square of the distance \( \frac{1}{d^2} \), the result was

\[
\phi_{d=t\,\text{cm}} = 20.8 \times \frac{(380)^2}{(t)^2} \text{n/cm}^2/\text{s}.
\]  

(11)

3.2. Neutron Yield Calculation. To calculate the results of equations (3) and (4), first, it must be calculated the terms of \( \sum_{E_F} \frac{\sigma(E)}{\rho \frac{dE}{dx}} \Delta E \) using the cross-section data of the reaction \( \sigma(E) \) as shown in Tables 1 and 2 (for reactions between proton with \(^{63}\text{Cu}\) and \(^{65}\text{Cu}\), respectively) and also the stopping power data \( \frac{1}{\rho} \frac{dE}{dx} \) as shown in Table 3. The result of the calculation \( \frac{\sigma(E)}{\rho \frac{dE}{dx}} \Delta E \) is listed in Tables 4 and 5.

| Table 1. Reaction cross-section of \(^{63}\text{Cu}(p,n)^{63}\text{Zn}\) |
|---|---|---|---|
| Energy, MeV | \( \sigma(E) \), mb | Energy, MeV | \( \sigma(E) \), mb |
| 4.5 | 49.6 | 9.0 | 367 |
| 5.0 | 89.4 | 9.5 | 404 |
| 5.5 | 184 | 10.0 | 440 |
| 6.0 | 205 | 10.5 | 421 |
| 6.5 | 248 | 11.0 | 440 |
| 7.0 | 262 | 11.5 | 480 |
| 7.5 | 313 | 12.0 | 466 |
| 8.0 | 334 | 12.5 | 437 |
| 8.5 | 360 | 13.0 | 455 |

| Table 2. Reaction cross-section of \(^{65}\text{Cu}(p,n)^{65}\text{Zn}\) |
|---|---|---|---|
| Energy, MeV | \( \sigma(E) \), mb | Energy, MeV | \( \sigma(E) \), mb |
| 3.0 | 14.0 | 8.5 | 559 |
| 3.5 | 65.4 | 9.0 | 697 |
| 4.0 | 49.6 | 9.5 | 644 |
| 4.5 | 95.1 | 10.0 | 728 |
| 5.0 | 221 | 10.5 | 731 |
| 5.5 | 346.8 | 11.0 | 736 |
| 6.0 | 422 | 11.5 | 716 |
| 6.5 | 433.4 | 12.0 | 700 |
| 7.0 | 492 | 12.5 | 560 |
| 7.5 | 533 | 13.0 | 456 |
| 8.0 | 575 |
Table 3. Stopping power of proton at Cu

| Kinetic Energy, MeV | Total Stopping Power, MeV cm²/g | Kinetic Energy, MeV | Total Stopping Power, MeV cm²/g |
|---------------------|---------------------------------|---------------------|---------------------------------|
| 2.50E+00            | 1.34E+02                        | 8.00E+00            | 5.46E+01                        |
| 3.00E+00            | 1.17E+02                        | 8.50E+00            | 5.20E+01                        |
| 3.50E+00            | 1.04E+02                        | 9.00E+00            | 4.97E+01                        |
| 4.00E+00            | 9.40E+01                        | 9.50E+00            | 4.76E+01                        |
| 4.50E+00            | 8.59E+01                        | 1.00E+01            | 4.57E+01                        |
| 5.00E+00            | 7.91E+01                        | 1.05E+01            | 4.39E+01                        |
| 5.50E+00            | 7.34E+01                        | 1.10E+01            | 4.23E+01                        |
| 6.00E+00            | 6.86E+01                        | 1.15E+01            | 4.08E+01                        |
| 6.50E+00            | 6.44E+01                        | 1.20E+01            | 3.94E+01                        |
| 7.00E+00            | 6.07E+01                        | 1.25E+01            | 3.82E+01                        |
| 7.50E+00            | 5.75E+01                        | 1.30E+01            | 3.70E+01                        |

Table 4. The value \( \frac{\sigma(E)}{\left(\frac{dE}{dx}\right)} \Delta E \) of \(^{63}\text{Cu}(p,n)^{63}\text{Zn}\) reaction

| Energy, MeV | \( \frac{\sigma(E)}{\left(\frac{dE}{dx}\right)} \) x10⁻²⁷ g | \( \Delta E \), MeV | \( \frac{\sigma(E)}{\left(\frac{dE}{dx}\right)} \) x10⁻²⁷ g |
|-------------|--------------------------------------------------|-------------------|---------------------------------|
| 4.5         | 0.52                                             | 9.0               | 6.28                            |
| 5.0         | 1.01                                             | 9.5               | 7.19                            |
| 5.5         | 2.22                                             | 10.0              | 8.12                            |
| 6.0         | 2.63                                             | 10.5              | 8.07                            |
| 6.5         | 3.36                                             | 11.0              | 9.50                            |
| 7.0         | 3.74                                             | 11.5              | 9.51                            |
| 7.5         | 4.70                                             | 12.0              | 9.62                            |
| 8.0         | 5.25                                             | 12.5              | 9.50                            |
| 8.5         | 5.90                                             | 13.0              | 10.16                           |

From the data in Table 4, it was obtained the value of \( \left(\sum_{E_{th}}^{E_{th}} \frac{\sigma(E)}{\left(\frac{dE}{dx}\right)} \Delta E\right) = 107.28 \times 10^{-27} \) g, and from equation (6) it was obtained neutron yield of the reaction \(^{63}\text{Cu}(p,n)^{63}\text{Zn}\) was

\[
Y_{63} = 5.9 \times 10^{40} \times I \times 0.69 \times 107.28 \times 10^{-27} = 437 \times 10^{13} \times I \text{ n/s}
\] (12)
Table 5. The value $\frac{\sigma(E)}{\frac{dE}{dx}} \Delta E$ of $^{65}$Cu(p,n)$^{65}$Zn reaction

| Kinetic Energy, MeV | $\frac{\sigma(E)}{\frac{dE}{dx}} \Delta E$, x10^{-27} g |
|--------------------|---------------------------------------------|
| 4.5                | 0.52                                       |
| 5.0                | 1.01                                       |
| 5.5                | 2.22                                       |
| 6.0                | 2.63                                       |
| 6.5                | 3.36                                       |
| 7.0                | 3.74                                       |
| 7.5                | 4.70                                       |
| 8.0                | 5.25                                       |
| 8.5                | 5.90                                       |

From the data in Table 5, it was obtained the value of $=169.95 \times 10^{-27}$ g, and from equation (7) it was obtained the yield of neutrons from $^{65}$Cu(p,n)$^{65}$Zn reaction was

$$Y_{65} = 5.9 \times 10^{40} \times I \times 0.31 \times 169.95 \times 10^{-27} = 311 \times 10^{13} \times I \text{ n/s.} \quad (13)$$

Furthermore, for proton $I = 1 \mu A = 10^{-6} \text{ A}$, then from equations (9) and (10) will be produced

$$Y_{65} = 437 \times 10^{13} \times 10^{9} \text{ n/second} = 4.37 \times 10^{9} \text{ n/s},$$

$$Y_{65} = 311 \times 10^{13} \times 10^{-6} \text{ n/s} = 3.11 \times 10^{9} \text{ n/s}.$$  

So the total neutron yield of a neutron reaction with Cu was

$$Y = Y_{63} + Y_{65} = (4.37 + 3.11) \times 10^{9} \text{ n/s} \approx 8.48 \times 10^{9} \text{ n/s}.$$  

3.3. Shielding Construction. From the calculation above, the yield of neutrons in the reaction between a 13 MeV proton and a current of 1 $\mu$A in copper pieces was $8.48 \times 10^{9} \text{ n/s}$. It was assumed that in the measurement of energy, neutron radiation was radiated from a point and spread in all directions. The chamber for placing the copper foils-for proton energy measurement was assumed to have a radius of $r = 4$ cm, then on the outer surface of the chamber, the value of the neutron flux will be based on equation (5) of

$$\phi_0 = \Phi_{4 \text{ cm}} = \frac{Y}{4\pi r^2} = \frac{8.48 \times 10^{9}}{100.48} \approx 0.8 \times 10^8 \text{n/cm}^2/\text{s}.$$  

The maximum neutron flux permitted on the outer side of the shielding (based on equation 11) was $20.8 \times \frac{(350)^2}{(t)^2} \text{n/cm}^2/\text{s} / \text{s};$ this was the value of $\phi_t$ in equation (9). Ordinary concrete shielding has $TVL = 19$ cm [14], then the value of $\Sigma_R$ according to equation (10), was $\Sigma_R = \frac{23}{19} \approx 0.12$. Finally, the shielding thickness value $t$ in equation (9) will fulfill the following equation

$$20.8 \times \frac{(350)^2}{(t)^2} = 0.8 \times 10^8 \times e^{-0.12t}$$

By using trial and error calculation, it was obtained that $t = 107$ cm. For practical consideration, the value of the thickness was taken to be $t = 110$ cm.
4. Conclusion
A proton energy measurement device will be operated in the DECY-13 Cyclotron, and for safety aspect purposes, a radiation shielding will be installed in the surrounding of the device. The shielding has been designed using ordinary K500 concrete material with a mass density of 2.3 gr/cm$^3$. The $TVL$ value of the concrete based on the reference is 19 cm. The thickness of the shielding has been calculated based on the radiation safety provisions. Namely, the safe neutron flux value for radiation workers is $25 \mu$Sv / hour, which is equivalent to a flux of $20.8$ n / cm$^2$ / sec at a distance of 350 cm from the center of the device. The result of the calculation that the thickness of the shielding is 107 cm, and for practical purposes, this value is rounded to be 110 cm.

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