proton current bombarding the targets was monitored in real-time using the Health Physics Watchdog [3] and the data was stored in a database. The integrated proton current (at Faraday Cup) and irradiation time were estimated to be 15489 μAh and 118 h respectively.

The activation pellets were retrieved after 72 hours cool down time (cyclotron shut down period) and assayed using a high purity germanium (HPGe) detector The activity of the $^{60}$Co in the cobalt pellet produced via the thermal neutron capture reaction $^{59}$Co(n, γ)$^{60}$Co was estimated. The thermal neutron fluence rate Φ [$cm^{-2}s^{-1}$] was evaluated using the formula described elsewhere [4].

$$\Phi = Q\eta^{-1}\sigma^{-1}N^{-1}[1-\exp(-\lambda ti)]^{-1}\exp(-\lambda td)^{-1}10^{-24} \tag{1a}$$

Where

$Q$ = γ-ray count rate of the irradiated cobalt pellet ($s^{-1}$)
$\sigma$ = thermal neutron capture cross section for $^{59}$Co = 37 barn (1barn = $10^{-24}$ $cm^2$)
$N$ = number of $^{59}$Co atoms in the pellet (equation 1b)
$\lambda$ = decay constant (equation 1c)
$ti$ = total irradiation time = 118h (Table 1)
$td$ = elapsed time between the end of irradiation and counting begin (cool down time) = 72 h

$$N = Lpkwa^{-1} \tag{1b}$$

Where

$L$ = Avogadro's number = $6.02 \times 10^{23}$ (atoms/mol)
$p$ = fraction of element of in a mixture (for $^{59}$Co, p =1)
$k$ = isotopic abundance (for $^{59}$Co, k =1)
$w$ = sample weight (g) (for $^{59}$Co pellet, w = 0.447 g)
$a$ = atomic weight of sample (for $^{59}$Co, a = 59)

$$\lambda = 0.693/T_{1/2} \tag{1c}$$

Where

$T_{1/2}$ = reaction product half life (for $^{60}$Co, $T_{1/2}$ = 5.6 y)

The average thermal neutron fluence $\phi_m$ at seven categories A, B, C, D, E and F were calculated to be $1.5\times10^4$, $3.4\times10^3$, $1.8\times10^3$, $1.1\times10^3$, $8.1\times10^2$ and $6.0\times10^2$ [$cm^{-2}s^{-1}$/μAh] respectively.

## Building Material of Cyclotron Components

We undertook a thorough check up of all cyclotron components located in the target vault (Figure 1) and found following materials as most important building materials: (a) Copper [5], (b) Aluminium-type 5083 [6], (c) stainless steel-types 304, 316, [7], (d) Brass-types 83600, 86300 [8]. The elemental compositions (percent) of the building materials are summarised in Table 1.

## Activity Calculations of Cyclotron Components

Important nucleonic properties major cyclotron building materials used in this report are presented in Table 3. The activities (A [$s^{-1}$]) generated in the cyclotron components via the thermal neutron capture is given as:

$$A = \sum_n \sigma_n N_n(1-\exp(-\lambda_n ti))\exp(-\lambda_n td)\Phi \tag{2a}$$

Table 1: Elemental compositions (percent) of the main cyclotron building materials considered in this work.

| Mat. | Copper Pipe | Brass (83600) | Brass (86300) | Steel (304) | Steel (316) | Alu (5083) |
|---|---|---|---|---|---|---|
| Al | --- | --- | 7.5 | --- | --- | 93 |
| C | --- | --- | --- | 0.08 | 0.08 | --- |
| Cr | --- | --- | --- | 20 | 18 | 0.25 |
| Cu | 99.9 | 84 | 66 | 0.35 | 0.35 | 0.1 |
| Fe | --- | 0.3 | 4 | 69 | 70 | 0.4 |
| Mg | --- | --- | --- | --- | --- | 4.9 |
| Mn | --- | --- | 5 | 2 | 2 | 1 |
| Mo | --- | --- | --- | 0.35 | 3 | --- |
| N | --- | --- | --- | 0.1 | 0.1 | --- |
| Ni | --- | 1 | 1 | 10.5 | 14 | --- |
| P | 0.1 | 0.05 | --- | 0.45 | 0.45 | --- |
| Pb | --- | 6 | 0.2 | --- | --- | --- |
| S | --- | 0.08 | --- | 0.03 | 0.03 | --- |
| Sb | --- | 0.25 | --- | --- | --- | --- |
| Si | --- | 0.005 | --- | 0.75 | 0.75 | --- |
| Sn | --- | 6 | 0.2 | --- | --- | |
| Ti | --- | --- | --- | --- | --- | 0.15 |
| Zn | --- | 6 | 28 | --- | --- | 0.25 |

Where

$\sigma_n$ = thermal neutron capture cross section for n$^{th}$ element in the cyclotron part of interest
$N_n$ = number of the atoms of the n$^{th}$ element (equation 1b)
$\lambda_n$ = decay constant of the n$^{th}$ reaction (thermal neutron capture) product (equation 1c)
$ti$ = irradiation time [h]
$td$ = cool down time [h]
$\Phi$ = thermal neutron fluence rate (equation 1a)

$$\Phi = \phi_m I \tag{2b}$$

Where

$\phi_m$ = normalised thermal neutron fluence rate of m$^{th}$ category and I = integrated Faraday Cup current [μAh]

## A Real Life Example

We have calculated the induced radioactivity in a piece of copper pipe, removed from the beam diagnostic port (BD) of target station T2.1 (Figure 1) after a continuous cyclotron operation (isotope production) time (ti) of 28 days, the integrated (Faraday Cup) current (I) was estimated to be 38800 μAh. The copper pipe (w = 500g) was taken out from the target station 2.2 (Figure 1) after a cool down time (td) of 24 hours. The normalised thermal neutron fluence ($\phi_m$) for category A was estimated as $3.4\times10^3$ [$cm^{-2}s^{-1}$/μAh]. By substituting the values of $\phi_m$ and I in equation 2b, the thermal neutron fluence rate at the location of copper pipe was calculated as:

$$\Phi_{Cu\text{-}Pipe} = 1.32\times10^8\ [cm^{-2}s^{-1}] \tag{3}$$

By using the list of cyclotron building materials (Table 1), the isotopic abundance of nuclide species (Table 2) in the material of interest and the formula (equation 1b) we estimated the number of $^{63}$Cu ($N_{63Cu}$), $^{65}$Cu ($N_{65Cu}$ ) and

$^{31}$P ($N_{31P}$) in the 500g copper tube to be $3.27\times10^{21}$, $1.46\times10^{21}$ and $9.72\times10^{18}$ respectively. Furthermore, by substituting the numerical values of $\Phi_{Cu\text{-}Pipe}$, ti, td, σ (Table 2) and the number of $N_{63Cu}$ (3b), $N_{65Cu}$ (3c) $N_{31P}$ atoms in equation 2a, the activities of the thermal neutron reaction products $A_{64Cu}$ , $A_{68Cu}$ and $A_{31P}$ were calculated as $10.8\times10^{8}$, 0.0 and $10.2\times10^{3}$ Bq respectively. By using the gamma dose conversion factor Γ [9] of $^{64}$Cu to be $3.6\times10^{-5}$[mSvh$^{-1}$MBq$^{-1}$m$^{-1}$] (Table 2) and the activity of $^{64}$Cu ($10.8\times10^{8}$ Bq), the gamma dose equivalent rate at 1m from the copper pipe was calculated to be 39μSv.h$^{-1}$. Evidently there was no contribution of $^{32}$P (a beta emitter) and $^{68}$Cu ($T_{1/2}$ = 5.1 min), which has completely decayed to nil during the 48 hours cool down period. The gamma dose equivalent rate at 1m from the centre of the copper pipe was estimated with a radiation survey meter was found to be 48μSv.h$^{-1}$.

Table 2: Important nucleonic properties of the main cyclotron building materials including nuclide species, abundance (a), thermal neutron capture cross sections (σ), daughter product of the (n, γ) reaction, half life and the gamma dose conversion factor Γ [mSv.h$^{-1}$MBq$^{-1}$.m$^{-1}$].

| **Nuclide Species** | **a [%]** | **σ [b]** | **React. Prod** | **Half Life** | **Γ (Dose Const)** |
|---|---|---|---|---|---|
| $^{27}$Al | 100 | 0.232 | $^{28}$Al | 2.25m | $2.4\times10^{-4}$ |
| $^{13}$C | 1.1 | 0.001 | $^{14}$C | 5730y | 0 |
| $^{50}$Cr | 4.3 | 15.9 | $^{51}$Cr | 27.7d | $6.3\times10^{-4}$ |
| $^{54}$Cr | 2.4 | 0.36 | $^{55}$Cr | 3.5m | 0 |
| $^{63}$Cu | 69.2 | 4.5 | $^{64}$Cu | 12.7h | $3.6\times10^{-5}$ |
| $^{65}$Cu | 30.8 | 2.17 | $^{66}$Cu | 5.1m | 0 |
| $^{54}$Fe | 5.9 | 2.3 | $^{55}$Fe | 2.73y | 0 |
| $^{58}$Fe | 0.28 | 1.2 | $^{59}$Fe | 44.5d | $1.8\times10^{-4}$ |
| $^{26}$Mg | 11 | 0.036 | $^{27}$Mg | 9.5m | $1.4\times10^{-4}$ |
| $^{55}$Mn | 100 | 13.3 | $^{56}$Mn | 2.58h | $2.5\times10^{-4}$ |
| $^{92}$Mo | 14.84 | 0.019 | $^{93}$Mo | 6.9h | $8.0\times10^{-5}$ |
| $^{98}$Mo | 24.13 | 0.14 | $^{99}$Mo | 2.75d | $3.0\times10^{-5}$ |
| $^{100}$Mo | 9.63 | 0.195 | $^{101}$Mo | 14.6m | $2.4\times10^{-4}$ |
| $^{58}$Ni | 68.27 | 4.6 | $^{59}$Ni | $7.6\times10^{4}$ y | 0 |
| $^{62}$Ni | 3.59 | 14.5 | $^{63}$Ni | 100y | 0 |
| $^{64}$Ni | 0.91 | 1.58 | $^{65}$Ni | 2.5h | $8.0\times10^{-5}$ |
| $^{31}$P | 100 | 0.18 | $^{32}$P | 14.3d | 0 |
| $^{204}$Pb | 1.4 | 0.66 | $^{205}$Pb | $1.5\times10^{7}$ y | $6.8\times10^{-5}$ |
| $^{206}$Pb | 52.4 | 0.49 | $^{207}$Pb | 3.3h | 0 |
| $^{34}$S | 4.21 | 0.29 | $^{35}$S | 87.2d | 0 |
| $^{36}$S | 0.02 | 0.15 | $^{37}$S | 5.05m | 0 |
| $^{121}$Sb | 57.4 | 5.9 | $^{122}$Sb | 2.7d | $8.2\times10^{-5}$ |
| $^{123}$Sb | 42.6 | 4.15 | $^{124}$Sb | 60.3d | $2.9\times10^{-4}$ |
| $^{30}$Si | 3.1 | 0.107 | $^{31}$Si | 2.62h | $1.3\times10^{-7}$ |
| $^{112}$Sn | 0.97 | 0.98 | $^{113}$Sn | 115d | $4.8\times10^{-5}$ |
| $^{120}$Sn | 32.59 | 0.14 | $^{121}$Sn | 27h | 0 |
| $^{122}$Sn | 4.63 | 0.18 | $^{123}$Sn | 129d | $1.0\times10^{-6}$ |
| $^{124}$Sn | 5.79 | 0.13 | $^{125}$Sn | 9.6d | $4.73\times10^{-5}$ |
| $^{50}$Ti | 5.4 | 0.177 | $^{51}$Ti | 5.8m | $7.1\times10^{-5}$ |
| $^{64}$Zn | 48.6 | 0.76 | $^{65}$Zn | 265d | $8.9\times10^{-5}$ |
| $^{68}$Zn | 18.8 | 1.0 | $^{69}$Zn | 56m | $1.2\times10^{-9}$ |
| $^{70}$Zn | 0.6 | 0.083 | $^{71}$Zn | 2.4m | 0 |

By applying the above method we have estimated the activities in 1kg aluminium (Type 5083) chunks induced by thermal neutrons during 1 year period (integrated Tgt.current $3.7\times10^{5}$ μAh) presented in Table 3.

Table 3: Predicted thermal neutron induced activation [Bq] in 1 kg aluminium chunks (Test Tag) for area categories A, B, C, D, E and F.

|  | Cr-51 | Zn-65 | Cu-64 | Fe-55 | Fe-59 |
|---|---|---|---|---|---|
| A | 4267 | 1159 | 473 | 295 | 29 |
| B | 1051 | 285 | 116 | 73 | 7 |
| C | 446 | 121 | 49 | 31 | 3 |
| D | 327 | 89 | 36 | 23 | 2 |
| E | 245 | 66 | 27 | 17 | 2 |
| F | 178 | 48 | 20 | 12 | 1 |

## SUMMARY AND CONCLUSIONS

A simple experimental method for the prediction of neutron induced component activation in high-current radioisotope production cyclotrons using tiny cobalt ($^{59}$Co) activation pellets is presented. The inner space of the target vault was divided in six categories based on thermal neutron fluence rate level. Using the thermal neutron fluence rate (evaluated from $^{60}$Co activities) and integrated target current we were able to predict the induced radioactivity generated in different cyclotron parts, commonly made of Copper, Aluminium, Brass and Steel. The gamma dose rate near the activated cyclotron part was calculated. The predicted induced activity (Bq) and the resulting gamma dose rate [μSv.h$^{-1}$] generated in a 500g copper pipe and 1kg aluminium chunks (test tag) exposed in the target vault was confirmed by measuring the gamma dose rate with a radiation survey instrument. This report ignored the activation products of fast neutron and proton induced reactions like, (n, 2n), (n, α), (p, n) and (p, 2n), prevalent in close proximity of targets, like collimator, Haver-foil window and the target station itself.

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