Neutron Field Inside a PET Cyclotron Vault Room

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Abstract

The neutron field around a Positron Emition Tomography cyclotron was investigated during $^{18}$F radioisotope production with an 18 MeV proton beam. In this study the Ion Beam Application cyclotron, model Cyclone 18/9, was utilized. Measurements were carried out with a Bonner sphere neutron spectrometer with pairs of thermoluminescent dosemeters (TLD600 and TLD700) as thermal neutron detector. The TLDs readouts were utilized to unfold the neutron spectra at three different positions inside the cyclotron’s vault room. With the spectra the Ambient dose equivalent was calculated. Neutron spectra unfolding were performed with the BUNKIUT code and the UTA4 response matrix. Neutron spectra were also determined by Monte Carlo calculations using a detailed model of cyclotron and vault room.

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1. INTRODUCTION

In some medical applications like linear accelerators [1] and Positron Emission Tomography, PET [2], neutrons arise as an undesirable product whose characterization in required for radiation protection purpose. PET is worldwide widely used for diagnostic purposes. PET is a non-invasive medical imaging technique used to determine the location and concentration of physiologically active compounds in human and animal bodies. The radionuclides used in this technique are $^{15}$O, $^{13}$N, $^{11}$C and $^{18}$F whose half lives are 20.385, 9.965, 2.037 and 109.77 minutes respectively; therefore, these radioisotopes must be produced in situ. Mostly of the cases they are generated using nuclear reactions with charged particles that produce an undesirable neutron field [3, 4].

During the interaction between an accelerated beam of charged particles and the target produce bremsstrahlung and characteristic x-rays, prompt $\gamma$-rays, neutrons and delayed radiation ($\beta$ and $\gamma$). Due to the lack of electric charge and the different ways neutrons interact with matter make neutron field characterization a difficult problem [3].

The fluorodeoxyglucose labeled with $^{18}$F is a PET widely used compound, the $^{18}$F radioisotope can be produced using $^{20}$Ne(d, $\alpha$)$^{18}$F and $^{18}$O(p, n)$^{18}$F nuclear reactions, whose Q-values are +2.792 and −2.437 MeV respectively. In the (p, n) reaction a 17.5 MeV proton beam and a target of $^{18}$O enriched water are utilized to produce $^{18}$F where an undesirable neutron field is generated. To assure the radiation protection protocols and to verify the shielding performance the neutron field must be characterized [2, 3].

In aim of this study was to determine the neutron spectra at three locations inside a PET cyclotron vault room during the production of $^{18}$F using the $^{18}$O(p, n)$^{18}$F nuclear reaction. The neutron spectra were determined through measurements and Monte Carlo calculations, with the spectra and the fluence-to-dose conversion factors, the ambient dose equivalent were also calculated.

2. MATERIALS AND METHODS

The PET cyclotron used in this investigation is a negative ion unshielded cyclotron located in the Navarra University Clinic, this is the Cyclone 18/9 model made by the Ion Beam Application Radioisotopes company. It is capable to accelerate protons and deuterons up to 18 and 9 MeV respectively. The cyclotron is located inside a 480 x 400 x 363 cm$^3$ vault room with 200 cm-thick concrete walls; in figure 1 is shown the cyclotron.

A 18 MeV proton beam was utilized to bombard $^{18}$O enriched water to produce $^{18}$F. During the measurements a 30 $\mu$A proton current, applied along 30.67 minutes, was utilized to bombard 2.2 grams of H$_2$O$^{18}$ target with 95% of $^{18}$O. Neutron spectra were measured at three sites, A, B and C, located at 181, 182 and 257 cm measured from the cyclotron center and at 90°, 180° and 0°, respectively, from the proton beam output direction. These locations, cyclotron and vault room are shown in figure 2. Neutron spectra were obtained using a Bonner sphere spectrometer (BSS) with pairs of thermoluminescent dosemeters, TLD600 and TLD700, as thermal neutron detector [4, 5]. The BSS was calibrated using a water-moderated $^{241}$AmBe; the net neutron signal was obtained through the difference between TLD600 and TLD700 readout using the area under the high-temperature peak in the TLDs glow curve [6].
Net neutron signals were used as input into BUNKIUT code with UTA4 response matrix to unfold the neutron spectra. The spheres in BSS are 0, 3, 5, 8, 10 and 12 inches-diameter whose
center was located at 144 cm above vault room floor and at 18 cm from vault walls.

Using a detailed model of vault room and cyclotron a Monte Carlo calculation, using the MCNP 4C code [7], was carried out to determine the neutron spectra at the sites where measurements were performed. In this stage the spectrum was also calculated at site D, located at 10 cm from target position and at 0° from proton beam direction. With the neutron spectra, $\Phi(E)$, and the ICRP 74 ambient dose equivalent-to-fluence conversion coefficients, $h^*(10)$, [8] the ambient dose equivalent, $H^*(10)$ was calculated.

### 3. RESULTS AND DISCUSSION

In figure 3 the measured neutron spectra at sites A, B, and C are shown. Here, the largest and

![Figure 3. Neutron spectra measured at sites A, B, and C.](image)

hardest spectrum is in site C with a peak around 1 MeV, it also shows the presence of epithermal and thermal neutrons ($E \leq 4.14E(-7)$ MeV) due to neutrons that lose energy through collisions with cyclotron body and vault room walls. At site A the peak is shifted to 0.1 MeV, its amplitude is lower to those located at the thermal region. In site B is also noticed the shift to lower energy;
here 0.1 MeV peak has approximately the same amplitude than those located at the epithermal region.

In figure 4 the calculated neutron spectra at sites A, B, C, and D are shown. Here the largest and

![Neutron spectra calculated at sites A, B, C, and D.](image)

hardest spectrum is observed at site D because is located closer to the target; the spectrum has a peak between 2 and 3 MeV. It shows epithermal neutrons and a small thermal neutron contribution; these are produced by those neutrons that collide with the cyclotron body. At site C the spectra shows a peak between 0.5 and 0.8 MeV, the presence of epithermal and thermal neutrons becomes more relevant in comparison with the peak due mainly to neutron interactions with cyclotron body and with the vault walls (room return). In site A the peak is noticed around 0.1 MeV whose amplitude is lower than thermal neutron peak. At location B a peak around 0.1 MeV is barely noticed, it amplitude is almost similar to those in the epithermal region. In the different sites can be observed that the peak is shifted to lower energies as the site goes far away from target position, also the room return effect is noticed by the presence of epithermal and
thermal neutrons. Measured and calculated spectra at A, B and C show similar features. Neutron spectra are alike to measurements performed in other PET cyclotron [3, 9], even when a different nuclear reaction and cyclotron design are different.

The peak observed at site D indicates the presence of evaporation neutrons produced during the nuclear reaction. These neutrons are scattered below 1 MeV due to inelastic scattering with the large amount of iron in the cyclotron body. The inelastic scattering threshold in $^{56}$Fe isotope, whose concentration in iron is the largest, is around 0.8 MeV, thus neutrons below 2 MeV are scattered with a smaller energy loss per collision, therefore the iron in the cyclotron body is the dominant effect in determining the energy upper section characteristics of neutron field inside vault room [10], this features is largely affected by the room return neutrons produced by the vault room concrete walls.

The calculated $H^*(10)$ in sites A, B, and C is $37 \pm 4$, $11 \pm 1$, and $377 \pm 38$ mSv/µA-h, the largest $H^*(10)$ is observed in site C, in sites A and B the $H^*(10)$ are lower due to neutron spectra modification produced by the cyclotron body and the neutron scattering in the room walls.

4. CONCLUSIONS

PET cyclotron is used to produce radioisotopes that are used as a non-invasive imaging technique for medical diagnosis purpose. Due its short half lives PET radioisotopes must be produced in situ and its production is accompanied with the generation of neutrons. The characterization of the undesirable neutron field is important to define health physics programs as well as the quality of neutron shield represented by the vault room walls.

A beam of 18 MeV protons is utilized to bombard a $^{18}$O enriched water target in the aim to produce $^{18}$F and the neutron field produced was measured at three locations inside a PET cyclotron vault room. Measurements were carried out with a Bonner sphere spectrometer with TLD600 and TLD700 pairs utilized as thermal neutrons.

Neutron spectra were also determined by Monte Carlo methods at the same sites were the measurements were carried out. In this stage neutron spectrum at 10 cm from target location was also calculated, no measurement was done in this site because radiation strength could permanently damage the TLDs.

During (p, n) nuclear reaction a large amount of evaporation neutrons are produced, this are largely affected by the presence of the large amount of iron in the cyclotron body that are modified by the room return neutrons produced by the concrete vault room walls.

Measured and calculated spectra, show the same behavior; neutron spectra obtained in sites close to target position shows a peak in the high energy region that is shifted to lower energies as the site is located beyond the target site, also the importance of epithermal and thermal neutrons is growing as the site is located beyond the target site where the room return effect becomes more important.
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REFERENCES