Study for the long-lived gamma background due to neutron emitting calibration reactions

Tanmoy Bar[1,2,*], *Dipali* Basak[1,2], *Sukhendu* Saha[1,2], *Lalit Kumar* Sahoo[1,2], and *Chinmay* Basu[1]

[1]Saha Institute of Nuclear Physics, 1/AF Bidhannagar, Saltlake, Kolkata - 700064, India
[2]Homi Bhabha National Institute, 2nd floor, BARC Training School Complex, Anushaktinagar, Mumbai - 400094, India

Abstract. In this article, a detailed theoretical investigation has been done on the long-lived gamma background due to neutron emitting reactions. It mainly focused on the experiments that will be used to calibrate energy with the terminal voltage of an upcoming Facility for Research in Experimental Nuclear Astrophysics (FRENA). Many reactions like (p, n), (p, γ) have been utilized in various accelerator facilities around the globe for energy calibration purposes. Neutron emitting reactions like ^{7}Li(p, n), ^{13}C(p, n), ^{19}F(p, n), ^{27}Al(p, n), etc. have been very commonly used. For such reactions, a significant number of neutrons produced from such experiments can interact with surrounding elements like copper, tantalum, stainless steel (SS304 and SS316), concrete materials, etc. These interactions may create long-lived gamma activity in the vicinity of the accelerator and detection area. Background gammas from these radioactive isotopes can interfere with gamma measurements in future experiments. The present study has been done to investigate those possibilities of gamma background which may occur due to the calibration study by neutron emitting experiments. Here ^{7}Li(p, n), ^{13}C(p, n), ^{19}F(p, n) and ^{27}Al(p, n) reactions having neutron threshold energies 1.8803, 3.2355, 4.2351, 5.8036 MeV respectively are chosen keeping in mind the proton energy available at the facility.

1 Introduction

Calibrated energy is one of the most essential requirements of any accelerator. For this purpose, many experiments like threshold, resonance, etc. have been performed in various accelerator facilities. Neutron threshold experiments are one of such which have been widely used around the globe. The current theoretical study is mainly focused on the upcoming accelerator facility called FRENA [1]. It is a high current low energy (0.2 - 3) MV tandetron accelerator primarily dedicated to experiments related to nuclear astrophysics with very low cross-sections (~pb to nb). It is currently located at Saha Institute of Nuclear Physics, Kolkata, INDIA. This machine can deliver a proton beam with an energy range between 400 keV to 6 MeV with maximum beam intensity >300 μA. A systematic study is very important to know the probable gamma background during and due to experiments specially when a neutron is one of the major emitting particles. Neutrons can easily interact with the surrounding material and form isotopes which is radioactive. Isotopes forming from such interactions

*e-mail: tanmoy.bar@saha.ac.in

Table 1. Emitting neutron energy range at threshold energies for different reactions.

	^{7}Li(p, n)	^{13}C(p, n)	^{19}F(p, n)	^{27}Al(p, n)
Neutron energy range (keV)	20.09 - 41.12	11.20 - 23.41	4.39 - 19.91	3.05 - 14.00

having significantly large half-lives can create additional gamma background for experiments that will be performed exactly after that. This study is important for the radiation safety of accelerator workers as well.

2 Study of different neutron emitting reactions

In this study, ^{7}Li(p, n), ^{13}C(p, n), ^{19}F(p, n) and ^{27}Al(p, n) reactions having neutron threshold energies 1.8803, 3.2355, 4.2351, 5.8036 MeV respectively are used keeping in mind the proton energy availability at FRENA. Most of the components of the accelerators are made of 304 and 316 Stainless steel alloy along with copper (Cu) and Tantalum (Ta). Apart from that Aluminium (Al), Calcium (Ca), Silicon (Si), and Oxygen (O) is also present in the vicinity. All stable isotopes of these elements have been considered during the investigation. Reaction cross-section has been calculated using Hauser-Feshbach statistical model code TALYS version 1.95 [2] and emitting neutron energy range at threshold has been estimated using kinematic calculation. Kinematic calculation for ^{7}Li(p, n) is shown in Figure 1 and list for all reactions have been mentioned in Table 1.

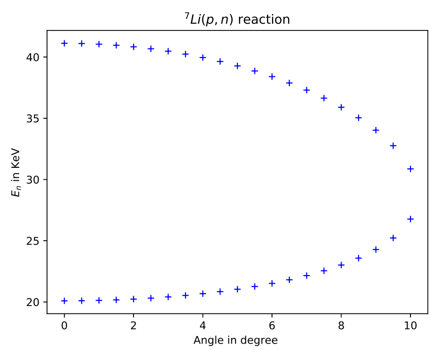

Figure 1. Neutron energy range of ^{7}Li(p, n) reaction at threshold energy (E_p = 1.8803 MeV).

3 Discussions on long lived activity

3.1 For proton at threshold energy

Neutrons emitting from these reactions at threshold energy as mentioned in Table 1 are within 50 keV. At this energy range, the most abundant tantalum isotope, ^{181}Ta (99.988%) is the only surrounding element that shows long-lived activity [3], having a half-life of more than 3 months. Fusion cross-section of ^{181}Ta with neutron in the energy range 10 - 40 keV is around $\sim 10^{-3}$mb. Gamma ray transition scheme is schematically shown in Figure 2.

^{181}Ta has half-live of ~114.74 days with most intense gamma rays of energies 1121.29 (35.24%), 1189.04 (16.49%), 1221.395 (27.23%), 1231.004 (11.62%) keV [4]. Complete list

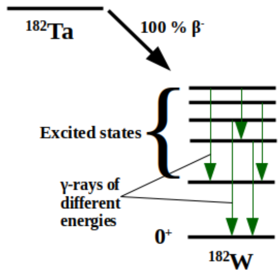

Figure 2. Schematic gamma transition scheme of ^{181}Ta.

of gamma having intensity greater than 1% along with cross-section value as calculated by TALYS for different neutron energy is shown in Table 2.

Table 2. List of gamma rays due to production of ^{182}Ta. Cross- section presented in the list is calculated by TALYS code and only gamma having intensity more than 1% are taken from NNDC [4].

Isotope	Abundance (%)	Neutron energy (keV)	Reaction product	Cross section (mb)	half life (days)	Daughter nucleus	γ-energy (keV)	γ intensity (%)
^{181}Ta	99.988	10	^{182}Ta	2.09×10^3	114.74	^{182}W	65.722	3.01
		20		1.34×10^3			67.749	42.9
		30		1.05×10^3			84.680	2.654
		40		8.69×10^2			100.106	14.2
							113.672	1.871
							152.429	7.02
							156.386	2.671
							179.393	3.119
							198.352	1.465
							222.109	7.57
							229.321	3.644
							264.074	3.612
							1001.7	2.086
							1121.29	35.24
							1189.04	16.49
							1221.395	27.23
							1231.004	11.62
							1257.407	1.51
							1289.145	1.37

3.2 For proton with higher energies

As the energy of the proton increases from the threshold value emitted neutron energy also gets increased, like for a 2 MeV proton, emitting neutrons will have energies between 16 - 232 keV. These energetic neutrons can interact with surrounding elements through different channels. In such a scenario, different isotopes will be produced which can contribute to the gamma background. As neutron energy goes beyond 350 keV, ^{54}Fe will produce ^{54}Mn having a half-life of 312 days. Most intense gamma-ray of ^{54}Mn is 834 keV (99.9%). Similarly, different isotopes will start to contribute as more and more reaction channels become accessible due to an increase in available neutron energy. Table 3 shows the contribution from different isotopes to the gamma background as neutron energy exceeds a specific value.

Table 3. Contribution of different isotopes due to increase in neutron energy. Isotopes in the vicinity and their natural abundance, produced isotopes after neutron capture and their half lives are listed in Columns 2 and 3. Column 4 and 5 indicated the final product and their most intense gamma rays along with relative intensity. Gamma energies and relative intensity are taken from NNDC [4].

Neutron Energy (keV)	Origin Isotope with Isotropic abundance (%)	Product after neutron capture with half life	Final product isotope	Most intense gamma rays(keV) with relative intensity (%)
> 350	^{54}Fe (5.85%)	^{54}Mn (312 days)	^{54}Cr	834 (99.9%)
> 400	^{58}Ni (68.07%)	^{58}Co (71 days)	^{58}Fe	810 (99.5%)
> 600	^{92}Mo (14.65%)	^{92}Nb (3.5 $\times 10^{7}$ years)	^{92}Zr	561 (100%),934 (74%)
> 850	^{40}Ca (96.94%)	^{40}K (1.3 $\times 10^{9}$ years)	^{40}Ar	1460 (10.66%)
> 900	^{50}Cr (4.35%)	^{50}V (2.6 $\times 10^{17}$ years)	^{50}Ti	1553 (99.3%)
> 1000	^{63}Cu (69.17%)	^{60}Co (5.27 years)	^{60}Ni	1173 (99.85%), 1332 (99.98%)
> 1600	^{98}Mo (24.29%)	^{95}Zr (64 days)	^{95}Nb	724 (44%), 756 (54%)
> 2500	^{94}Mo (9.19%)	^{94}Nb (2.1 $\times 10^{4}$ years)	^{94}Mo	702 (99.81%), 871 (99.89%)
> 3000	^{60}Ni (26.3%)	^{60}Co (5.27 years)	^{60}Ni	1173 (99.85%), 1332 (99.98%)

4 Conclusion

In this work, it was found that neutron emission occurs in the intermediate energy range for protons with energy close to the threshold value. For such reactions, only concerning element present in the nearby place is ^{181}Ta. But, in FRENA or any other accelerator facility tantalum is used mainly at the beam dump or in the faraday cup. Now, these components can be kept far away from the scattering region and can be shielded with lead bricks, High-Density Polyethylene (HDPE), and other conventional elements. In this way, detectors can be kept at a safe distance from gamma rays coming from the tantalum dump. Apart from tantalum, ^{58}Fe present in the visinity also form ^{59}Fe having half-life ~44 days with most intense gamma rays of energies 1099 keV(56.5%), 1291 keV(43.2%) etc. But the natural abundance of ^{58}Fe is only ~0.28%, so its contribution to the background may not be of much trouble. For reactions with protons at higher energy than the threshold, more isotopes need to be monitored as mentioned in Table 3.

References

[1] FRENA, $http://www.saha.ac.in/web/frena-about-frena.$
[2] TALYS Code, $https://tendl.web.psi.ch/tendl2019/talys.html$
[3] Tanmoy Bar et al., arXiv:2203.01995v1 [nucl-ex] 3 Mar 2022.
[4] National Nuclear Data Centre, https://www.nndc.bnl.gov/