Radiation environment in low energy accelerator for astrophysical studies

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Transmitted dose through different thicknesses of ordinary concrete placed at different distances from the target has been evaluated using simple Moyer model. It has been observed that though the projectile energy is low, significant neutron and gamma doses are produced at beam currents as high as 500 µA for protons. Some radioisotopes with half-lives of the order of a few months are produced with activities of the order 10¹⁰-10¹¹ Bq.

Keywords: Neutron doses, Gamma doses, EMPIRE code, Concrete shield

1 Introduction

Study of astro-particle physics is an evolving subject attracting young researchers for the last few decades. In order to study the mechanism of production of heavy proton-rich isotopes, fusion of heavy ions and other processes, (p,γ) reactions are mostly investigated in the energy range of ~1-6 MeV and (α,γ) reactions in the energy range of ~ 5-15 MeV along with heavy ion induced reactions at low energies.

Saha Institute of Nuclear Physics, Kolkata, India is setting up a Facility for Research in Experimental Nuclear Astrophysics (FRENA) to provide opportunities in astrophysics research. As in the case of all accelerator facilities, design construction and design safety review of this accelerator calls for radiation environment around this accelerator be assessed for operating parameters that would lead to maximum radiation field. As the design of the accelerator facility is not finalized, a preliminary set of calculations has been done for a proposed design to determine its suitability for operation.

2 Computational Procedure

The accelerator is designed to accelerate protons, ³He, alpha particles and heavy ions from ⁷Li to ¹⁹⁷Au. But for the present calculations we have considered protons, ³He and alpha particle projectiles only, interacting with some common targets like Al, Fe / Ge and Ta. The source terms for energy differential emission cross section of neutrons and gamma rays are calculated using the nuclear reaction model code¹ EMPIRE 2.18. From the emission cross sections so obtained the energy differential neutron and gamma yield are determined taking into account the range and stopping power of proton projectile in the target and the total number of target atoms available for the interaction for maximum design currents of 500 µA for protons and 100 µA for ³He and alpha particles. The double differential yields of neutrons and gamma rays are determined from the energy spectra considering the emission to be isotropic in the laboratory frame as the projectile energy is low. These are then converted to dose rates at different angles using the ICRP fluence to dose conversion coefficients². The unattenuated neutron and gamma dose rates at 1 m from the target in the forward direction are computed from the double differential dose rates by integrating over the entire emission energy range. The transmitted dose rates through a concrete shield are then evaluated for maximum design currents for protons, ³He and alpha particles using the simplified Moyer formula. For this purpose the shield is considered to be made of ordinary concrete with a density of 2.35 g/cc. As the projectile energy is low, build up of neutron and gamma doses are not taken into account. Partial radioactive inventory is prepared from the estimated induced activity of some radiotoxic isotopes.

2.1 Nuclear reaction model

The code EMPIRE 2.18 calculates preequilibrium (PEQ) and evaporation (EQ) emission cross sections of neutrons, protons, alpha particles and one light ion along with gamma emission. Emission of multiple neutron, proton and alpha ejectiles as permissible by
energy and momentum conservation of the reaction system can be considered. For calculating PEQ emission cross sections different combinations of several standard PEQ models like multi-step direct (MSD), multi-step compound (MSC), exciton (DEGAS/PCROSS) can be chosen. But at the projectile energies involved in the present work PEQ contribution is negligible and evaporation yield only is taken into account. EQ emission cross section for neutrons is determined using the statistical Hauser-Feshbach (HF) theory in EMPIRE. The exact angular momentum and parity coupling are done considering full $\gamma$-cascade in the residual nuclei. Gamma ray emission cross section is calculated by considering E1, E2 and M1 transitions in the HF model. An arbitrary mixture of giant multipole resonance (Brink Axel hypothesis) and of the Weisskopf single particle model can be used. Relative contribution of both the approaches is invoked through an input parameter $t$. EMPIRE 2.18 has a provision to calculate the level density of the residual nuclide following evaporation using three different formalisms. In the present study, the Gilbert-Cameron model for EQ reactions has been used.

EMPIRE does not give angular distribution for the emitted particles or photons. In such a situation and since we are dealing with low energy nucleon or light ion induced reactions, the angular distribution of the nucleons and the photons are taken to be isotropic. From the double differential emission cross section for neutrons and gamma rays, thus obtained, double differential yields are calculated.

### 2.2 Moyer formula

The double differential neutron and gamma yield, $Y(\varepsilon,\theta)$, in a given direction $\theta$ are folded with ICRP fluence to dose conversion factors, $F(\varepsilon)$, and then integrated over the emission energy range to obtain the unattenuated dose $[H_0(\theta)]$ at a distance of 1 m. The transmitted equivalent dose $[H(\theta)]$ due to neutrons or photons outside a shield is given by:

$$r^2 H(\theta) = H_0(\theta) \exp(-d/\lambda) \quad \ldots (1)$$

where $r =$ distance of the point of observation (outside the shield) from the source

$H =$ equivalent dose at the point of observation

$H_0 =$ equivalent dose at unit distance from the source

$d =$ thickness of the shield

$\lambda =$ attenuation length for the combination of radiation type and shield material considered.

### 3 Results

Figure 1 shows the gamma energy spectra for 6 MeV photon induced reaction on the three targets Al, Ge and Ta. We see that photon emission from Ta target is significantly lower than in the case of other two targets. Range of 6 MeV protons in Al, Ge and Ta are 259, 176.7 and 86.4 $\mu$m, respectively. From the calculated energy differential cross section the total photon yield for the three targets are determined for the entire proton range in the target. Figure 2 shows the energy spectra of emitted neutrons from the Ge and Ta targets for 6 MeV proton induced reaction. For Al target, neutron emission at this proton energy has been found to be negligible. In Fig. 3 we have shown the gamma and neutron energy spectra for $^3$He induced reaction on Al target as for $^3$He projectile, yield of neutrons and gammas is maximum from Al target. The unattenuated neutron and photon doses for the $^{27}$Al, $^{70}$Ge, $^{56}$Fe, $^{181}$Ta targets and p and $^3$He projectile combinations are given in Table 1. In the other cases of target projectile combinations considered in this study, these doses are not significant.

![Gamma spectra from 6 MeV proton induced reaction on Al, Ge and Ta targets](image)
The transmitted dose due to gamma radiation through different thicknesses of concrete and for different distances (d) of the point of observation from the target is shown in Fig. 4 for p + Al reaction at 6 MeV. In the proposed layout of the facility the minimum distance from the target to a point accessible to the users is approximately 8.08 m. It has been found that a thickness of about 105 cm of concrete is required to reduce the dose at this point below the permissible limit. For total neutron+gamma doses at maximum operating parameter, a shield thickness of more than 1.2 metres will be necessary to reduce the dose below permissible limit.
The induced activity of isotopes like $^{56}\text{Co}$ ($t_{1/2} = 77.27$ d), $^{181}\text{W}$ ($t_{1/2} = 121.2$ d) grows to $\sim 10^{10}$-$10^{11}$ Bq after 100 days of irradiation are given in Table 2.

4 Conclusions

The data presented in this paper are based on the preliminary calculations considering the proposed geometric layout of the accelerator facility. Final results for the transmitted dose through the shield and the radiation environment inside the accelerator hall will probably have low to moderate variation compared to the present result depending on the change in the design of the facility. However, preliminary radiation safety analyses indicate that the proposed accelerator can be safely commissioned in the proposed site if provided with adequate shield.

References