LINAC-BASED PHOTONUCLEAR APPLICATIONS AT THE IDAHO ACCELERATOR CENTER

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In this paper, current Idaho Accelerator Center (IAC) activities based on the exploitation of high energy bremsstrahlung photons generated by linear electron accelerators will be reviewed. These beams are used to induce photonuclear interactions for a wide variety of applications in materials science, activation analysis, medical research, and nuclear technology. Most of the exploited phenomena are governed by the familiar giant dipole resonance cross section in nuclei. By proper target and converter design, optimization of photon and photoneutron production can be achieved, allowing radiation fields produced with both photons and neutrons to be used for medical isotope production and for fission product transmutation. The latter provides a specific application example that supports long-term fission product waste management. Using high-energy, high-power electron accelerators, we can demonstrate transmutation of radio-toxic, long-lived fission products (LLFP) such as ^{99}Tc and ^{129}I into short lived species. The latest experimental and simulation results will be presented.

Keywords: Bremsstrahlung; photonuclear; photoneutron; transmutation.

1. Introduction

Bremsstrahlung photons,^{1,2} produced by the interaction of electrons with a high Z converter, have a unique continuous energy spectrum that can be "tuned" to some extent by electron beam energy and converter geometry. Beam energies of a few tens of MeV can produce photons that couple strongly with the giant dipole resonance region in nuclei to produce particle emission and hence neutron production and transmutation reactions. As a result, mixed fields (photons and neutrons) are produced in which neutron to photon ratios and their energy distributions may be varied by electron beam energy and converter design.

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Of particular interest is applying transmutation phenomena to problems in nuclear waste management and production of useful radioisotopes. In the former case, the interest is in using transmutation to reduce the environmental burden of the long-lived fission product (LLFP) ^{129}I (15.7 million years half-life) and ^{99}Tc (211,000 years half-life). These nuclei are the major risk/dose components of the LLFP and are dominant considerations for sustainable long-term nuclear waste management. These nuclides can be transmuted to shorter half-life species by (n,γ) and (γ,n) reactions: in the case of ^{129}I , both reactions result in short half-life transmutation products. The $^{129}\text{I}(n,\gamma)^{130}\text{I}$ reaction results in ^{130}I , which has a 12.36 hour half-life, and the $^{129}\text{I}(\gamma,n)^{128}\text{I}$ reaction results in ^{128}I , which has a 25 minute half-life.

In this work, we want to explore the efficiency of using two-particle irradiation, photons and neutrons, produced in a common converter target. The major issue is proper target design to optimize both photon and neutron production. This must be done in such a way that thermal and mechanical properties of the system are practical and cost effective. An illustration of the mixed irradiation idea is shown in Fig. 1 as an example of resolving the ^{129}I and ^{99}Tc problem in LLFP.

Fig. 1. Mixed-field transmutation scheme.

2. Monte Carlo Simulations

Monte Carlo calculations follow the history of individual particles so that the average behavior is inferred from the collective effect of single particles. Particle production fields (photon and neutron) can be predicted, and nuclear reaction rates can be obtained. After source configuration and target construction, one needs to enable physics processes such as bremsstrahlung radiation and photonuclear interactions to track photons and neutrons. Particle fluence (Fig. 2) and spatial distributions (Fig. 3) through a volume or surface can be obtained.

Fig. 2. MCNPX photon flux distribution (left) and neutron flux distribution (right) by a 40 MeV e^- beam incident on a 0.5 cm W converter.

Fig. 3. (Left) Photon spatial distribution due to a 40 MeV e^- beam incident on a 4 mm thick W converter. (Right) Neutron spatial distribution due to a 40 MeV e^- beam incident on a 10 cm x 10 cm W converter.

To estimate the efficiency of ^{99}Tc transmutation by photoneutrons, a Cu–W converter was used with different moderators. The purpose of the moderator is to thermalize neutrons so that one can make full use of the resonance cross section (Fig. 4 left). Lead (Pb), water (H_2O) and heavy water (D_2O) moderators were used for simulations. A pellet shaped ^{99}Tc sample was placed on the surface of the cylindrical converter to minimize the influence by photons. The MCNPX results show that the ^{99}Tc transmutation rate is the highest when the target is surrounded by water. Comparison of the neutron flux with or without the moderator reveals the reason why water yields the highest reaction rate (Fig. 4 Right). Water can also serve as a coolant.

Fig. 4. (Left) $^{99}\text{Tc}(n,\gamma)^{100}\text{Tc}$ cross-section.³ (Right) MCNPX neutron flux distribution with and without water moderator.

Since ^{129}I can be transmuted in a mixed-field of both photons and neutrons, MCNPX simulations were performed to determine the optimum target geometry for the highest photon and neutron-induced reaction rates. Five different converter thicknesses (0.1, 0.5, 1, 2, 5 cm) were examined with an iodine target surrounded with water (Fig. 5 Left).

Fig. 5. (Left) MCNPX simulation layout. (Right) MCNPX iodine reaction rate vs. converter thickness.

The $^{129}\text{I}(\gamma,n)^{128}\text{I}$ reaction yield reaches its maximum when the converter thickness is ~ 0.5 cm. The $^{129}\text{I}(n,\gamma)^{130}\text{I}$ reaction yield reaches its maximum when the converter thickness is ~ 2 cm (Fig. 5 Right). Thus we can improve total burn-up efficiency of ^{129}I by 20% with a thin converter design (0.5 cm). In the case of thick converter design (> 2 cm), where the high energy electron has to be stopped, we can double the burn-up yield by a mixed-field irradiation scheme. It should also be noted that the iodine can be circulated throughout the moderator to take advantage of the neutron flux throughout the volume,

increasing the net transmutation rate. The optimum configurations for this work are yet to be determined.

3. Experimental Results

In order to understand the neutron and photon radiation field produced by a high energy electron beam, a tungsten-copper (80% W, 20% Cu) cylinder was used as a converter. MCNPX simulations were performed to predict the photon and neutron fluxes and resulting photonuclear conversion rates inside the cylinder. Experimentally, pure Cu and Mn alloy wires were used for photon and neutron flux monitoring. Activation wires were placed inside holes drilled at different distances away from the axis of the electron beam as shown in Fig. 6. The samples were irradiated for 30 minutes using a 40 MeV electron beam at 110 W average power. By comparing MCNPX and experimental results, we can see from Fig. 7 that photon and neutron production predictions agree well with the experimental data on ^{64}Cu and ^{56}Mn activities.

Fig. 6. Target geometry and wire positions in a tungsten converter.

Fig. 7. Comparison of MCNPX and experimental results: (Left) ^{64}Cu activities from the $^{65}\text{Cu}(\gamma, n)^{64}\text{Cu}$ reaction; (Right) ^{56}Mn activities from the $^{55}\text{Mn}(n, \gamma)^{56}\text{Mn}$ reaction.

4. Conclusions

A series of preliminary experiments has been conducted to assess the spatial distribution and intensity of photon and neutron fields using high power electron linacs. Several target geometries and calculation schemes have been studied. Activity measurement routines and operating schemes have been developed. With the aid of simulation codes and the experiments, more applications of mixed-field transmutation schemes will be investigated.

Acknowledgments

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