2021 TIPP
Poster 713

TOPAS Simulations for Estimating ^{48}V Yields of Natural Titanium Foil Irradiation

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ABSTRACT

In this work, we simulate the irradiation of natural titanium foils via TOPAS, a Geant4-based Monte Carlo program [1]. The results are compared to the experimental yield of foils bombarded with 18 MeV protons in a beamstop of the IBA Cyclone 18/9 at the University of Chicago Cyclotron Facility.

Natural titanium foils can be used to produce β^+ emitter vanadium-48 (^{48}V), which could be used in positron emission tomography (PET). Due to its 16-day half-life, ^{48}V has potential application in long-term monitoring and longitudinal studies of disease progression. While foils are often irradiated via solid target system, medical cyclotrons lacking these systems often have components that can be manipulated for this purpose, such as placing thin foils in a beamstop, making production of ^{48}V feasible for a wider range of facilities.

TOPAS results produced 11-18% difference compared to experimental results and a 54% difference compared to theoretical calculations, indicating that factors such as foil angle may have lowered experimental yields.

EXPERIMENTAL ^{48}V PRODUCTION

12 µm natural titanium foils are molded into a 'cup' and placed in the beam stop. The target is irradiated with 18 MeV protons at 10 or 20 µA for 0.5 to 8.5 hours. Longer irradiation times and stronger currents have been used but are not included for comparison as irradiations >8 hours are broken into segments and difficult to simulate. After irradiation, the target is left for some time (<2 days) to allow short-lived isotopes to decay. The target is then assayed. A gamma-ray spectrum is taken via NaI well counter to observe the radioisotopes present and verify the presence of ^{48}V [2].

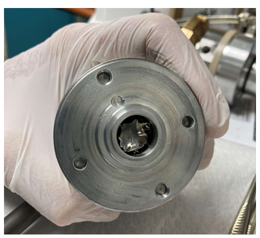
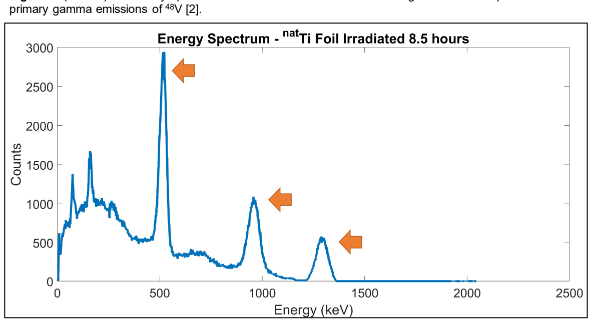


Figure 1: (top left) Beam stop with foils inserted. **Figure 2:** (top right) Natural titanium foil molded into a cup **Figure 3:** (bottom) Gamm-ray spectrum of foil irradiated for 8.5 hours. Orange arrows correspond to the primary gamma emissions of ^{48}V [2].



TOPAS SIMULATIONS

The cyclotron beam is simulated based on parameters in the literature [3]. The beam profile is observed by simulating a LYSO panel at the irradiation plane. The beam width is taken as the diameter of the beam intensity profile, 0.54 cm.

To validate the simulations, the cross section of the $^{nat}Ti(p,n)^{48}V$ reaction is measured by irradiating a foil stack. The foil thicknesses are adjusted so that 1 MeV is lost per foil. A histogram of incident energies per foil is acquired and used to find the average incident proton energy. The foil stack is irradiated with 10^8 protons using several different physics lists to determine an optimal list. The ions generated per foil are counted and converted to cross section with Equation 1. N_T is ions generated; A is the atomic mass; N_A is Avogadro's Number; N_P is the number of incident protons; ρ is target density; and t is target thickness.

$$\sigma = \frac{N_T A}{N_A N_p \rho t} \quad (1)$$

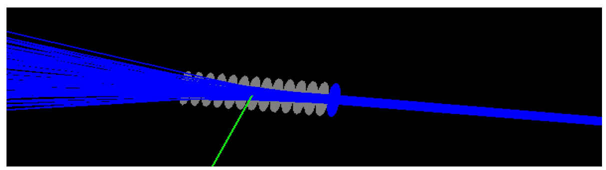
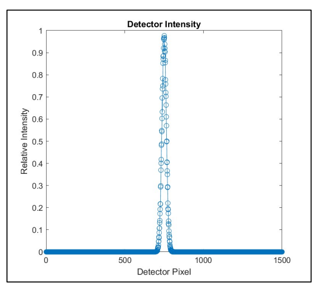
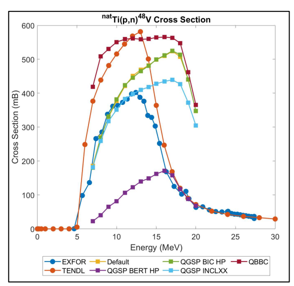


Figure 4: (top) Simulated foil stack irradiated with 1000 protons (blue). The green is a gamma ray produced in the foil. **Figure 5:** (bottom left) Beam profile of incident protons in LYSO detector. **Figure 6:** (bottom right) Cross sections produced per physics list, with comparison to experimental data [4] and theoretical calculations [5].





Using the above beam parameters and physics list, the natural titanium foil 'cup' is simulated and irradiated with 10^8 protons. The ions generated in the volume are counted and converted to activity using Equation 2, where λ is the decay constant, I is the beam current, and t is time irradiated; the latter two constants are implemented for comparison to experimental yields.

$$A(t) = \frac{N_T \lambda t I(e^{\lambda t})}{N_p} \quad (2)$$

REFERENCES

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RESULTS

Cross Section: At lower energies, the default list (yellow, Figure 6) and most QGSP lists (green, blue) produce a cross section comparable to those in the literature (dark blue, orange), while the QBBC (red) list overestimates the cross section and QGSP-BERT-HP (purple) underestimate the cross section. At higher energies, TOPAS overestimates the cross section for all physics lists except QGSP-BERT-HP.

Yield Comparison: Figure 7 and Table 1 shows a comparison of radioactive yields generated in simulation and experimentally by irradiating cup-shaped foils at 18 MeV. The simulated activity for a single foil was similar to experimental values: when using the QGSP BIC HP physics list, yields different by 11% at 10 µA current and 18% at 20 µA. Results were substantially different when using the QGSP BERT HP list, indicating the variability of results based on physics list. This difference is due to the differing cross sections for each of these lists at 18 MeV.

Geometry	Simulation Counts	Activity (10 µA, 1 hr)	Activity (20 µA, 1 hr)	Experimental Yield (1 hr)	%Diff.	% Increase Compared to QGSP BERT HP
1 Foil	33448 ±94	0.102 ±0.0003	0.204 ±0.0006	10 uA: 91.5 µCi 20 uA: 171 µCi	11% 18%	364%
2 Foils	67234 ±95	0.205 ±0.0003	0.409 ±0.0006	-		357%

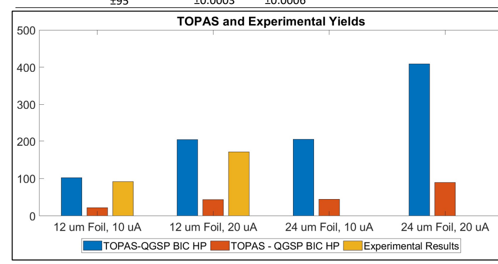

Table 1: (top) Yields per current and time irradiated in TOPAS and comparison to experimental results. **Figure 7:** (left) Graph of yield results. QGSP BIC HP produces results comparable to experimental yield, while the QGSP BIC HP list produces much smaller yields.

DISCUSSION AND FUTURE WORK

TOPAS provides a reasonable estimate of radioactivity generated by cyclotron-based irradiation of natural titanium foils. While an apparent over-estimation of the cross section for commonly used physics lists limits the possibility of construing an exact radioactivity measurement, this tool can be used to estimate the radioactivity in order to guide experiments and inform experimental outcomes.

Future work will seek a more appropriate physics list; the list used was shown to have a significant impact on the resulting yield. Future work will also focus on validating these results with yields from other targets produced in the same cyclotron and corresponding TOPAS simulations, including yields from longer times and higher currents.

ACKNOWLEDGEMENTS

This project was supported in part by the Cancer Center Support Grant (P30 CA14599) of the UCCCC; the Pilot Seed Grant funding provided by the Department of Radiology; and by the National Physical Sciences Consortium as part of the NPSC Fellowship.

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