Proton Beam Energy Characterization

Lauren A. Marus[1], J.W. Engle, K.D. John, E.R. Birnbaum, F.M. Nortier

Los Alamos National Laboratory, Los Alamos, New Mexico, USA

Introduction

The Los Alamos Isotope Production Facility (IPF) is actively engaged in the development of isotope production technologies that can utilize its 100 MeV proton beam. Characterization of the proton beam energy and current is vital for optimizing isotope production and accurately conducting research at the IPF.

Motivation

In order to monitor beam intensity during research irradiations, aluminum foils are interspersed in experimental stacks. A theoretical yield of ^{22}Na from ^{27}Al(p,x)^{22}Na reactions is calculated using MCNP6 (Monte Carlo N-Particle), TRIM (Transport of Ions in Matter), and Andersen & Ziegler (A&Z) [1] computational models. For some recent experiments, experimentally measured activities did not match computational predictions. This discrepancy motivated further experimental investigations including a direct time-of-flight measurement of the proton beam energy upstream of the target stack. The Isotope Production Program now tracks the beam energy and current by a complement of experimental and computational methods described below.

Material and Methods

A stacked-foil activation technique, utilizing aluminum monitor foils [2] in conjunction with a direct time-of-flight measurement helps define the current and energy of the proton beam. Theoretical yields of ^{22}Na activity generated in the Al monitor foils are compared with experimental measurements. Additionally, MCNP, TRIM, and A&Z computational simulations are compared with one another and with experimental data.

Experimental Approach

Thin foils (0.254mm) of high purity aluminum are encapsulated in kapton tape and stacked with Tb foils in between aluminum degraders. Following irradiation, the Al foils are assayed using γ-spectroscopy on calibrated HPGe detectors in the Chemistry Division countroom at LANL. We use the well-characterized ^{27}Al(p,x)^{22}Na energy dependent production cross section [3] to calculate a predicted yield of ^{22}Na in each foil.

[1]Corresponding author, E-mail: lamarus@lanl.gov

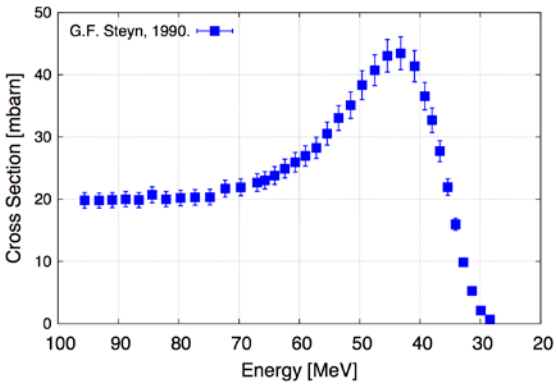

FIGURE 1. Published cross section for ^{27}Al(p,x)^{22}Na in Al monitor foils, from [3]

Details of the experimental activity determination and associated uncertainties have been addressed previously [4].

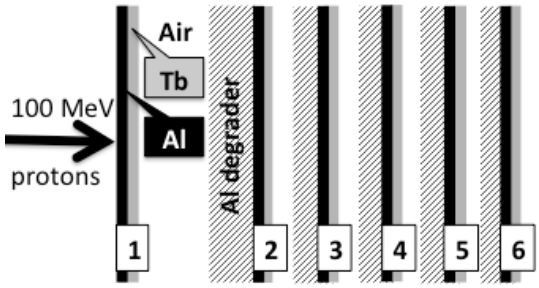

FIGURE 2. Schematic of the stacked target used in experiment. Not shown, but accounted for in calculations are: the target holder, vacuum-isolation window, and cooling water upstream of the foil stack.

The nominally stated beam parameters are 100 MeV and 100–120 nA for the foil stack irradiation experiments. Time-of-flight measurements performed in the month of January 2014 revealed beam energy of 99.1 ± 0.5 MeV.

Computational Simulations

Andersen & Zeigler (A&Z) is a deterministic method and also the simplest of the three computational methods considered. While the mean energy degradation can be calculated using the A&Z formalism, the beam current attenuation cannot. Consequentially, A&Z will also lack the ability to account for a broadening in the beam energy that a stochastic method affords. Addi-

tionally, A&Z does not account for nuclear recoil or contributions from secondary interactions.

TRIM uses a stochastic based method to calculate the stopping range of incident particles applying Bethe-Block formalisms. TRIM, like A&Z, does not include contributions from nuclear recoil or contributions from secondary interactions. Computationally, TRIM is a very expensive code to run. TRIM is able to calculate a broadening in the energy of the beam; however, beam attenuation predictions are much less reliable. TRIM determines the overall beam attenuation in the whole stack to be less than one percent, whereas 7–10 % is expected.

MCNP6 is arguably the most sophisticated approach to modeling the physics of the experiment. It also uses a stochastic procedure for calculation, adopting the Cascade-Exciton Model (CEM03) to track particles. The physics card is enabled in the MCNP input to track light ion recoils. Contributions from neutron and proton secondary particle interactions are included, although their contribution is minimal. For both MCNP and TRIM, the proton beam is simulated as a pencil beam.

To find the current, an F4 volumetric tally of proton flux from MCNP simulation is matched to the experimental current for the first foil in the stack. Subsequent foil currents are calculated relative to the first foil based on MCNP predictions for beam attenuation. The equation used for calculating the current from the experimental activity is [5]:

$$\sigma_i(E) = 2.678\times10^{-10}\frac{A\lambda N_i}{I\rho x\left(1-e^{-\lambda t}\right)}$$

where:

$\sigma_i(E)$ is the cross section for the process, [mbarns]

A is the atomic mass of the target [amu]

N_i is the is the number of product nuclei present at End-of-Bombardment

I is the average beam current, [μA]

ρ is the density of the target material, [g/cc]

x is the target thickness, [cm]

λ is the decay constant, [s^{-1}]

t is the irradiation time, [s]

For each foil in the experimental stack, we also have a statistically driven broadening of the incident energy. The beam energy is modeled as a Gaussian distribution, with the tallies for each energy bin determining the parameters of the fit. TABLE 1 and FIG. 3 summarize the mean energy and standard deviation of the energy for each aluminum monitor foil.

	Mean Energy [MeV] (standard deviation)		
Foil Number	MCNP	TRIM	A&Z
1	89.5 (0.4)	89.4 (0.4)	89.4
2	80.2 (0.6)	79.9 (0.6)	79.9
3	70.8 (0.8)	70.3 (0.8)	70.2
4	62.5 (0.9)	61.9 (0.9)	61.8
5	53.5 (1.0)	52.6 (1.1)	52.4
6	43.2 (1.3)	41.8 (1.3)	41.6

TABLE 1. Energy distribution of Tb foil stack for 99.1 MeV incident beam energy

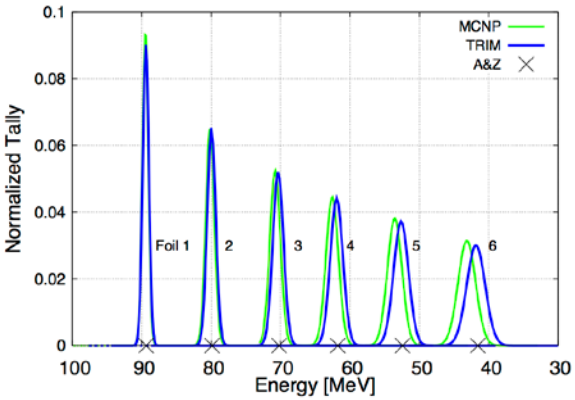

FIGURE 3. Energy distribution and simulation comparison for MCNP, TRIM, and A&Z Tb foil stack. Note the energy distribution is normalized to the individual foil, not between foils.

To address the energy distribution, we calculate an effective or weighted cross-section. It is especially important to account for energy broadening in regions where the associated excitation function varies rapidly. In the excitation function in FIG. 1, we see a strong variation in the energy range from 30–65 MeV, the energy region covered by the last 3 foils in the stack. Cross section weighting also accounts for the mean energy variation within each foil.

The excitation function will overlay the Gaussian shaped flux distribution, giving rise to a lateral distribution where incrementally weighted values of the cross section are determined by the flux tally of the corresponding energy bin.

With the effective cross section and the current at each of the foils, it is straight-forward to calculate the number of ^{22}Na atoms created and

[1]Corresponding author, E-mail: lamarus@lanl.gov

the activity of each foil using the previously stated equation.

Results and Conclusion

The general trend in the amount of activity produced follows the shape of the excitation function for the $^{27}Al(p,x)^{22}Na$ reaction; compare FIG. 1 with FIG. 4. Small shifts in the incident energy upstream trickle down to produce much more pronounced shifts in the energy range of foils towards the back of the foil stack. The characteristic "rolling over" of the activity seen in the experimental foils indicates that the 6th foil must be in the energy region below 45 MeV, where the peak of the excitation function occurs.

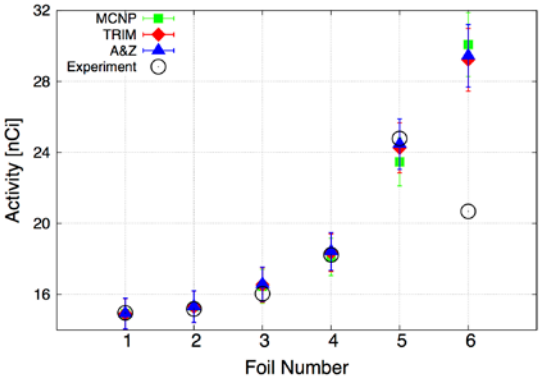

FIGURE 4. Calculated vs. measured activity for Al monitor foils

Conservatively, computational simulations are able to accurately determine the proton beam's energy for an energy range from 100 to 50 MeV. As the beam degrades below 50 MeV, computational simulations diverge from experimentally observed energies by over-predicting the energy. This observation has been noted in past studies [6,7] that compare the stacked foil technique with stopping-power based calculations.

A complement of experimental and computational predictions allows for energy determinations at several points within target stacks. While this study focuses on an Al-Tb foil stack, the analysis of a similar Al-Th foil stack resulted in the same conclusions.

Although we do not have a concurrent time-of-flight energy measurement at the time of the foil stack experiments, it is reasonable to assume that the energy at the time of the stacked foil experiments was also lower than the assumed energy of 100 MeV. Computational simulations developed in this work firmly support this assumption.

Various computational models are able to predict with good agreement the energy as a function of depth for complex foil stack geometries. Their predictions diverge as the beam energy distribution broadens and statistical uncertainties propagate. A careful inspection of the codes reveals that these discrepancies likely originate from minute differences between the cross sections and stopping power tables that MCNP and TRIM/A&Z use respectively.

References

1. H.H. Andersen and J.F. Ziegler: *Hydrogen Stopping Power and Ranges in All Elements*. Pergamon, 1977.
2. J.B. Cumming: *Annu. Rev. Nucl. Sci.* **13**, pp.261–286, 1963.
3. G.F. Steyn, S.J. Mills, F.M. Nortier et al.: *Appl. Radiat. Isot.* **41**(3), pp. 315–325, 1990.
4. J.W. Engle, S.G. Mashnik, J.W. Weidner et al: *Phys. Rev. C* **88**, 014604, 2013.
5. IAEA-TecDoc-1211 (2001). *Charged Particle Cross-Section Database for Medical Radioisotope Production: Diagnostic Radioisotopes and Monitor Reactions.*
6. J.H. Kim, H. Park, S. Kim, J.S. Lee, K.S. Chun: *J. Korean Phys. Soc.* **48**, pp. 755–758, 2006.
7. M.U. Khandaker et al.: *Int. J. Phys. Sci.* **6**(13), pp. 3168–3174, 2011.

Acknowledgements

Many thanks to the Isotope Production Group for its guidance and technical ingenuity that made many parts of this study possible. Funding provided by DOE Office of Science, Nuclear Physics.

[1]Corresponding author, E-mail: lamarus@lanl.gov