# UNM Dosimetry of Materials Irradiated at LANSCE

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1 Measurement of Proton Fluence by Activation of Aluminum Foils

Aluminium foils are placed into the 800 MeV proton beam to be used as dosimeters. The aluminum foils have sizes approximately 1x2 cm^2, 1x1 cm^2, and 2x2 cm^2 depending on the size of the test sample with which they are associated. In the interaction of the aluminum with the proton beam p, the element ^{22}Na is produced. The ^{22}Na decays via $\beta^+ \sim 90.32\%$ of the time and electron capture $\sim 9.62\%$ of the time to excited ^{22}Ne, which then decays with a half-life of 2.602 years. The excited ^{22}Ne quickly de-excites by emitting a gamma ray of energy 1274.5 keV as shown in Figure 1. The positron annihilates with an electron in the source or the cladding and emits gamma ray of 511 keV. The gamma energy spectrum is acquired with a gamma-ray spectrometer.

We measure the total activity of the foil to compute the fluence. The rate of accumulation is given by

$$^{27}Al \xrightarrow{p} \, ^{22}Na \xrightarrow{\lambda} \, ^{22}Ne$$
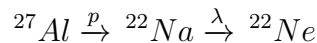
The rate of decay of ^{22}Na is given by

$$\frac{dN(^{22}Na)}{dt} = \varphi N(^{27}Al)\sigma - \lambda N(^{22}Na)$$

where φ is the proton flux, σ is the total cross section for the production of ^{22}Na from proton-induced reactions on aluminum foil, and λ is the decay
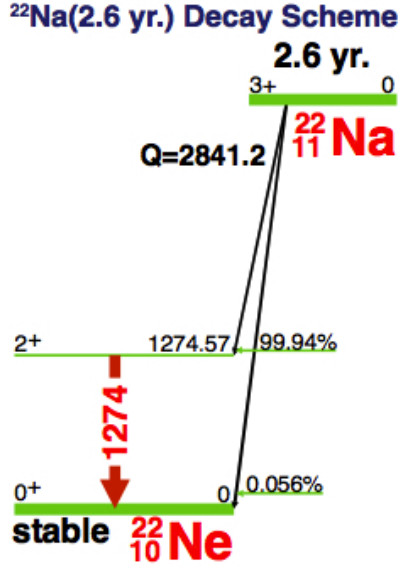
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Figure 1: Decay spectra of the ^{22}Na

constant that relates to the half-life $t_{1/2}$ as $\lambda = \frac{ln2}{t_{1/2}}$. We assume that $N(^{27}Al)$ is constant and given by

$$N(^{27}Al) = \frac{N_A \times P \times W}{M_A}$$

where N_A is Avogadro's number, P is the purity of the aluminum foil, W is the mass of foil in grams, and M_A is the atomic mass of aluminum. We assume that $N(^{22}Na)(t = 0) = 0$, and we use high purity aluminum with purity of 99.5%. By solving the equation for these initial conditions we obtain

$$N(^{22}Na) = \frac{\phi N(^{27}Al)\sigma(1 - e^{-\lambda t})}{\lambda}.$$

The activity A of the irradiated foil in the absence of the beam is given by

$$A = -\frac{dN(^{22}Na)}{dt} = \lambda N(^{22}Na).$$

The activity of a foil irradiated by protons for a period T and then measured after an elapsed time t_e is

$$A(t_e) = \varphi N(^{27}Al)\sigma(1 - e^{-\lambda T})e^{-\lambda t_e}$$

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Immediately after proton irradiation, $t_e = t_0 = 0$, and we can write

$$A(t_0) = \varphi N(^{27}Al)\sigma(1 - e^{-\lambda T}).$$

Hence the expression for the activity immediately after irradiation reduces to

$$A(t_e) = A(t_0)e^{-\lambda t_e}.$$

In our setup the foil is left to decay for an elapsed time t_e and then measured for an interval of time $t_c = t_f - t_e$.

The average activity during the interval is given by

$$\overline{A(t_c)} = \frac{A(t_0)}{t_c} \int_{t_e}^{t_f} e^{-\lambda t} dt = \frac{A(t_e)}{\lambda t_c}(1 - e^{-\lambda t_c}).$$

Thus,

$$A(t_e) = \frac{\overline{A(t_c)}\lambda t_c}{(1 - e^{-\lambda t_c})}.$$

We measure $\overline{A(t_c)}$ and compute $A(t_e)$ and $A(t_0)$. Using $A(t_0) = \varphi N(^{27}Al)\sigma(1 - e^{-\lambda T})$, where t_0 is the time at the end of irradiation, we can compute the flux

$$\phi = \frac{A(t_0)}{N(^{27}Al)\sigma(1 - e^{-\lambda T})} = \frac{A(t_e)e^{\lambda t_e}}{N(^{27}Al)\sigma(1 - e^{-\lambda T})}.$$

We then compute Φ, the proton fluence in protons/cm^2, through $\Phi = \phi T$.

2   Calibration of the Gamma Ray Spectrometer

We use an ORTEC GEM45P4-76-SMP gamma ray detector system and an ORTEC DSPEC-50 Multi Channel Analyzer (MCA) to collect these data in counts/unit time/channel. To calculate the activity at a particular energy we need to convert these data into decays/unit time at a given energy. Our calibration source's spectrum ranges from 59.5 keV to 1836.1keV and has eleven energy peaks distributed over this range. We also need the detection efficiency of the HPGe spectrometer's detector system as a function of energy. The efficiency of the detector system relates the number of gamma rays emitted from the source to the number of gamma rays collected in the full energy peak area.
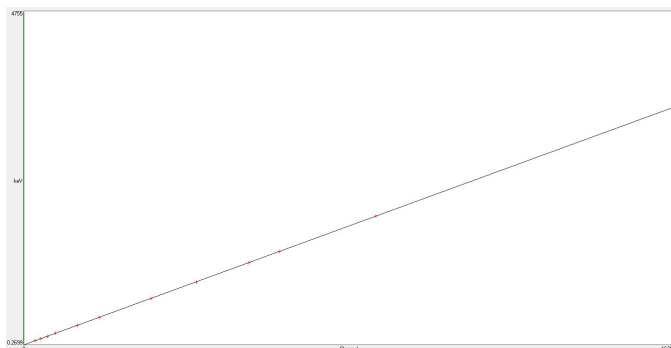
Figure 2: Calibration of energy versus channel number, captured as a screen-shot from the ORTEC spectrometer.

2.1 Energy Calibrations

There are two energy calibration functions, (1) the energy vs. channel number, and (2) the peak shape (or FWHM) versus energy. The inputs to these functions are a spectrum or series of spectra with isolated peaks distributed over the energy range of interest, and an analysis gamma-ray library or table of peak energies. The formula for energy vs. channel number is

$$E(C) = a_1 + a_2 C + a_3 C^2$$

where E is the energy, the a_i are coefficients, and C is the channel number. We obtain these coefficients a_i by selecting the Auto Calibration option and fitting the energy spectrum of the calibration source with a quadratic polynomial. Figure 2 shows the fitted curve of calibrated energy versus channel number. The coefficients obtained are $a_1 =0.207$ keV, $a_2 = 0.207$ keV/channel, and $a_3 = -3.914 \times 10^{-9}$ keV/channel^2.

The formula for FWHM versus channel number is

$$F(C) = b_1 + b_2 C + b_3 C^2$$

where F is FWHM in channels, the b_i are coefficients, and C is the channel number. To calculate the FWHM in energy, $F(E)$, we use the formula

$$F(E) = F(C)(a_2 + a_3 C)$$

where $F(C)$ is FWHM in channels at channel C, C is channel number, and a_2 and a_3 are given as above. Calibration begins with collection of the spectrum
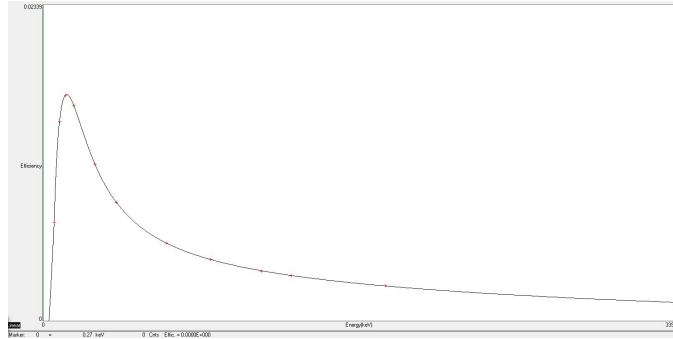
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Figure 3: Calibration of efficiency versus energy, captured as a screenshot from the ORTEC spectrometer.

of the calibration source with its isolated peaks. We use the Mixed Gamma Standard point source (peak energies are in keV, shown in the parentheses), which contains Am-241(59.54), Cd-109 (88.03), Co-57 (122.07), Ce-139 (165.85), Hg-203 (279.17), Sn-113 (391.69), Cs-137 (661.66), Y-88 (898.02), Co-60 (1173.24), Co-60 (1332.5), and Y-88 (1836.01). It has a gamma-ray emission rate of 3 microCi. We use the Auto Calibration mode, which performs a complete energy and FWHM calibration on the displayed spectrum using the working library. Auto Calibration searches for all the major peaks in the spectrum, and then this peak list is compared to the library peak list to find the calibration that gives the best match.

2.2 Efficiency Calibrations

The HPGe detector system efficiency includes effects from the detector itself, the detector source geometry, the materials surrounding the detector, and absorption in the source material. Efficiency is a function of energy, and our p-type germanium detector (ORTEC GEM Series) has a maximum efficiency at about 150 keV. To perform the efficiency calibration, we use the spectrum of the calibration radionuclides, the initial source strengths, and the calibration dates. These data are entered by the ORTEC custom software GammaVision-32. We use a 6-term polynomial to fit the natural logarithm of efficiency ϵ versus energy E:

$$\epsilon = e^{\left(\sum\limits_{i=1}^{6} a_i E^{2-i} \right)}.$$

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The a_i are fitting coefficients. This function is optimized for a p-type detector. Figure 3 shows the fitted curve of calibrated efficiency versus energy for energies from 0 to 3396 keV. The coefficients a_i, in order of increasing index i are -0.321305, -5.652440, 0.569694, -0.072035, 0.003970, and -0.000092 respectively. GammaVision-32 recalls the Calibration Certificate table (provided by Mixed Gamma Standard) of entries and performs a calibration based on the data in the nuclide calibration table, and once the procedure is complete it displays the graph and calibration table.

3 Fluence Measurement Uncertainties

The primary sources of uncertainty on the measurement of proton fluence are the uncertainty in the measurement of the activity of ^{22}Na (σ_A); the uncertainty in the measurement of production cross-section of ^{22}Na (σ_C); the uncertainty in the measurement of mass of the Al foil (σ_W); the uncertainty in the measurement of dimensions of the Al foil (σ_D); and the uncertainty in the measurement of exposure counting time during the proton irradiation (σ_T).

3.1 Uncertainty in the Measurement of the Activity

The total uncertainty in the measurement of the activity is determined by summing in quadrature the individual uncertainties from the various analysis components[1]. These contributions are σ_{count}, the counting uncertainty; σ_{nor}, the normally distributed uncertainty; σ_{rsum}, the random summing uncertainty; σ_{abs}, the absorption uncertainty; σ_{nuc}, the nuclide uncertainty; σ_{eff}, the efficiency uncertainty; σ_{geo}, the geometry uncertainty; and σ_{uni}, the uniformly distributed uncertainty. All of the components of uncertainty are computed at the 1-sigma level and printed out in the activity report.
The counting uncertainty (σ_{count}), is given by σ_{GA}, the uncertainty in the gross area and σ_{BA}, the uncertainty in the background area added in quadrature:

$$\sigma_{count} = \sqrt{\sigma_{GA}^2 + \sigma_{BA}^2}.$$

Gross area error is given by the square root of the gross area. Background area error is given by the square root of ($\frac{Background\ area \times peak\ width}{Width\ of\ low\ average + Width\ of\ high\ average}$). The Gamma Vision software calculates this uncertainty and shows it in the analysis report.

3.2 Estimation of Uncertainties

The estimated uncertainty in the measurement of the production cross-section of ^{22}Na is about 2.6% [2]. A typical aluminum foil was weighed to ± 0.1 mg accuracy, and its contribution to the uncertainty in the measurement is less than 1%. The counting uncertainty is highly dependent on the amount of time the Aluminum foil is measured by the gamma ray spectrometer. If the sample is counted for 10 minutes, the overall measurement uncertainty is on the order of 10%. If the sample is counted for 12 hours or longer the overall uncertainty reduces to $2-3\%$. The dimensions of the foil were measured to the precision of ± 0.001 cm and contribute uncertainty to the measurement of about 0.5%. The uncertainty in the measurement of counting time is less than 0.1%.

4   Beam Profile Measurement

A measurement of the LANSCE proton beam profile may be found at link http://panda.unm.edu/NUPAC_NMCPP/atlas_pixel/research/pages/ documents/Beam_Profile_UNM.pdf. The following result serves as a confirmation.

We insert transverse to the beam a 2x2 cm^2 aluminum foil segmented into sixteen individual squares and expose it to a fluence of approximately 4×10^{15} protons/cm^2. We then measure the activity of each individual square separately and measure the proton fluence received by it.

Figure 4 shows the resulting histogram of proton beam profile received by each foil. The aluminum square centered on position (1.25 cm, 0.75 cm) received the maximum proton fluence and indicates the centre of the beam spot. The beam intensity is distributed over an area of about 2 cm^2, and the hot beam spot is located within ~ 0.5 cm^2. The maximum fluence received by the aluminum square is about 1.02×10^{15} protons/cm^2 and its total uncertainty in measurement is less than 1.5%.

5   References

[1] ORTEC, GammaVision-32, Gamma-Ray Spectrum Analysis and MCA Emulator for Microsoft Windows User's Manual (pp.286-292).

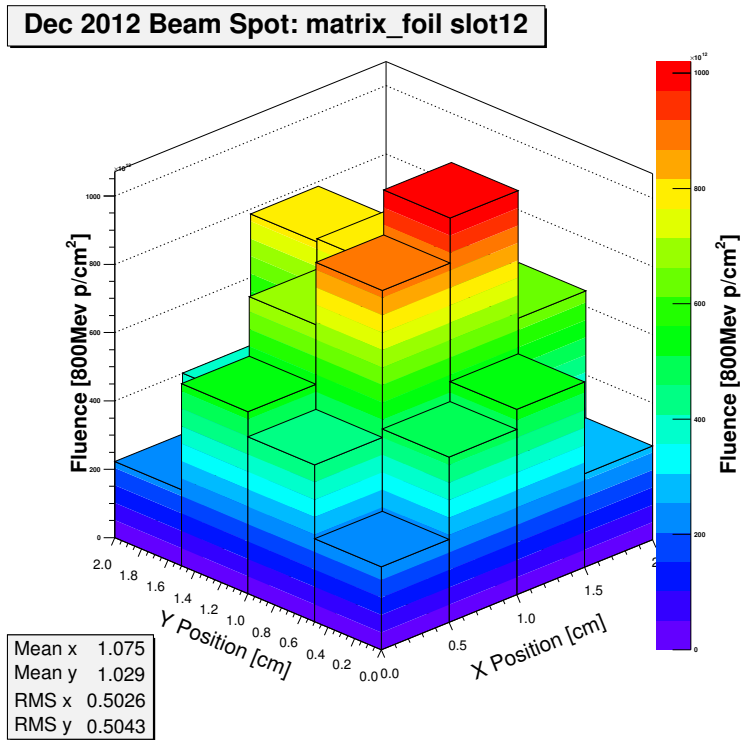[2] G.L. Morgan et al., Nucl. Instr. and Meth. in Phys. Res. B 211 (2003) 297304.

Figure 4: proton beam profile in XY plane as a function of proton fluence.