To: Fermilab ESH&Q Radiation Safety
From: Kun Liu, Dustin Keller
Re: SpinQuest Ammonia Target Activation Calculation
Date: January 24, 2024

This memo provides a calculation of the expected beam activation of the target material (frozen ammonia or deuterated ammonia, NH_3/ND_3). The long-lived radionuclides considered in this memo are ^{3}H and ^{7}Be as the products of 120 GeV proton beam and ^{14}N in the target.

I. Target Specifications

The SpinQuest experiment uses frozen ammonia (NH_3) or deuterated ammonia (ND_3) as the target material. The target material has a shape of small beads with 1-2 mm diameters. During normal operation, the target material is loosely packed in the cylindrical target cup, which is soaked in liquid Helium and placed in the beam. The target insert has three identical target cups, only two of them will be filled with target material, with the third cup empty for background subtraction. Each target cup can contain up to 14g of frozen ammonia. The detailed specifications of the frozen ammonia target is summarized in Table 1.

Target Material	Molecular Weight (M)	Density (ρ)	Mass per cup (m)	Length (L)
NH_3	17.031 g/mol	0.917 g/cm^3	14 g	7.9 cm

Table 1: SpinQuest target material specifications.

With the information above, we calculate the volume V, the surface area S and the ^{14}N number density N using the following formula:

$$V = \frac{m}{\rho}, \tag{1}$$

$$S = \frac{V}{L}, \tag{2}$$

$$N = \frac{\rho N_A}{M}, \tag{3}$$

where $N_A = 6.02 \times 10^{23}$ atoms/mol is the Avagadro's number.

Inserting numbers from Table 1 into Eqn (1), (2) and (3), the volume, surface area and ^{14}N number density of the target material are calculated and summarized in Table 2.

Target Material	Volume (V)	Surface Area (S)	^{14}N number density (N)
NH_3	15.267 cm^3	1.933 cm^2	3.241×10^{22} atoms/cm^3

Table 2: SpinQuest target material propteries.

II. Expected Beam Conditions

The SpinQuest experiment uses the 120 GeV proton beam from the Main Injector. The shielding of the SpinQuet experiment is evaluated for 120 GeV proton at 6.0×10^{14} per hour, which is equivalent to 1.0×10^{13} protons per pulse and 60 pulses per hour [1]. Each target cup can be used for no more than 7 days before it becomes totally depleted and must be swapped out. This limit is defined by the total accumulated dose per cell. The material cannot be polarized well beyond this threshold. Therefore the maximum time and proton dose each target cup can receive are:

$$t_{irr} = 604800 \text{ s},$$

$$\phi(t) = 1.008 \times 10^{17} \text{ protons}.$$

III. Calculation of the activity of ^{3}H and ^{7}Be

According to Eqn 7.5 from FERMILAB-TM-1834 [2], the number density of a given radionuclide can be obtained by

$$n(t) = \frac{N\sigma\phi}{\lambda}(1 - e^{-\lambda t}), \tag{4}$$

where N is the number density of target atoms (1/cm^3), σ is the production cross section (cm^2), $\phi = \frac{\phi(t)}{St_{irr}}$ is the flux density $(1/(\text{cm}^2 s))$, $\lambda = \frac{\ln 2}{t_{1/2}}$ is the delay constant $(1/s)$, and $t = t_{irr}$ is the total irradiation time (s).

From Table 8.2 of FERMILAB-TM-1834 [2], we find the half lives of ^{3}H and ^{7}Be to be $t_{1/2-H} = 12.32$ years $= 388523520s$ and $t_{1/2-Be} = 53.2$ days $= 4596480s$. The production cross-sections can also be found in Table 8.2 of FERMILAB-TM-1834 [2], $\sigma_H = 30\text{mb} = 3 \times 10^{-26}\text{cm}^2$ and $\sigma_{Be} = 10\text{mb} = 1 \times 10^{-26}\text{cm}^2$.

Inserting all the numbers into Eqn (4), we obtain the number density for ^{3}H and ^{7}Be after 7 days of beam

$$n_H(t_{irr}) = 5.068 \times 10^{13} \text{ cm}^{-3},$$

$$n_{Be}(t_{irr}) = 1.615 \times 10^{13} \text{ cm}^{-3}.$$

We can then obtain the activity of ^{3}H and ^{7}Be using $a(t_{irr}) = \lambda n(t_{irr})$ (Eqn 7.7 from FERMILAB-TM-1834 [2])

$$a_H(t_{irr}) = 9.04 \times 10^4 \text{ Bq/cm}^3,$$

$$a_{Be}(t_{irr}) = 2.44 \times 10^6 \text{ Bq/cm}^3.$$

Multiply the activity with the volume of the target, and convert from Becquerel (Bq) to Curie (Ci), we have the volume activation for ^{3}H and ^{7}Be after 7 days of beam on one target cup with 14g of NH_3.

$$a_H(t_{irr})_V = 37\ \mu\text{Ci},$$

$$a_{Be}(t_{irr})_V = 1005\ \mu\text{Ci}.$$

IV. Expected Radiation Classification

The γ constant for ^{7}Be is 0.0344 mrem/hr per mCi @ 1.0 meter [3], therefore one cup of target material (14g) is expected to have a dose-rate of 0.37 mrem/hr when measured at 1ft. The dose-rate from ^{3}H is negligible at 1ft.

For normal operations, we expect to have two target cups loaded with 14g of ammonia in each cup. Therefore we will have a total of 28g of depleted material after each target change, and the total dose-rate will be 0.74 mrem/hr.

References

[1] Neutrino Muon Beamline Shielding Assessment Addendum for E1039, SEAQUEST-doc-7671-v1

[2] Fermilab Report TM-1834, Revision 16, ESH-doc-1007-v12

[3] Health Physics & Radiological Health Handbook, 3rd Ed. [Baltimore, MD; Williams & Wilkins, 1998], p. 6-9