

Introduction

The subject of tritium production in the Antiproton Source Collection lens was raised in the mid-1980s during the design phase of the pbar source [1]. Interest in it has recurred during development of the proton lens [2] and in recent investigations to determine the feasibility of liquid lithium collection lenses for the pbar source [3] and a muon collider project.

Calculations for tritium and beryllium 7 production on lithium suffer from a lack of information on medium and high energy cross section data. In addition, knowledge of the energy spectrum within the target vault is based upon calculations. Knowledge of the low energy spectrum, important for tritium production on lithium, is limited, if not non-existent.

For Collider Run II, effort is to be applied to improve the performance of the solid lithium lens [4]. Historically, examination of failed lithium lenses has not been pursued because they have been fairly radioactive and because they are thought to contain significant quantities of the radionuclides tritium and beryllium 7. The development of methods to examine failed lithium lenses may be desirable so that the specific causes of failure can be discovered. From such studies, design improvements can be incorporated with the goal of achieving lens performances goals related to Collider Run II.

The purpose of the lithium irradiation experiment is to determine the production rates of radioisotopes tritium and beryllium 7 within the lithium lens in its operating in its operating environment.

Experiment Plan

The lithium compound $\text{LiOH}\cdot\text{H}_2\text{O}$ was found to be available from a chemical supply company [5] in a couple isotopically enriched forms, 95% Li^6 and 97% Li^7 . A third sample of this compound was obtained from another chemical supply company [6] and was 99.55% Li^7 . These compounds were measured and mixed with measured quantities of water and were placed in polyethylene bottles which were placed in the target vault on a test stand made for this purpose. The solutions were intended to be saturated and some care was taken to ensure that the solids had dissolved and were in solution. The resulting LiOH solutions were approximately 5.3 normal. Three polyethylene bottles filled with DI water were also installed on the

test stand. The intention was to provide for production of tritium and beryllium 7 in a controlled volume containing known quantities of lithium 6, lithium 7, and oxygen.

There were several concerns regarding the handling and analysis of radioactive caustic solutions in this experiment. The Activation Analysis Lab believed that the pH of the LiOH solutions which could cause an interference in the tritium scintillation counting based upon scintillation cocktail literature. Test reagents of the type to be irradiated were obtained by the Activation Analysis Lab. The test reagents were used to practice mixing saturated solutions and to determine that the reaction was endothermic. The 5.3 normal LiOH solutions were neutralized with 1 N HCl and it was determined that the reaction was well-behaved (endothermic). Scintillation counting was performed on a number of trials of solutions with various pHs and it was verified that the solutions would need to be neutral or slightly acidic to obtain accurate results. With these trials, it was found that the LiOH solutions could be handled safely with ordinary laboratory precautions.

There was some concern that the polyethylene bottles may not survive in the vault environment and might begin to leak. A drip collection pan was made and installed on the test fixture for this purpose. Fortunately, the bottles survived the test though they were discolored. The bottle caps, while intact, were found to be very brittle.

The possibility was considered that water in the matrix could result in the production of low energy neutrons which could drastically increase the production of tritium on lithium 6. However, the lithium conductor in the collection lens is positioned within a cooling water jacket. The use of LiOH solutions for this experiment should lead to a conservative conclusion because, if there is an effect, it is likely that tritium production would be exaggerated rather than suppressed.

A separate reason for using a water matrix is related to the method in which tritium can be measured. One could produce tritium in lithium metal, but then a complication arises in how to measure it. Tritium is a low energy beta emitter (12 KeV) whose presence within a metal matrix could not be detected and measured directly by external counting techniques because of self-shielding. The tritium would somehow have to be extracted from the metal and then collected and processed so that it could be measured. This could perhaps be accomplished by reacting lithium metal in water, burning the resulting hydrogen gas under controlled

conditions, condensing and cooling the resulting water vapor, and finally analyzing the resulting water from tritium. In addition, the resulting lithium hydroxide in a water solution could be neutralized and analyzed. The total tritium produced would be that measured in the condensed water and in the lithium hydroxide solution.

The laboratory has the capability to measure tritium in water solutions using liquid scintillation counting. In the target vault environment, in addition to activation of the lithium and oxygen atoms, there is also a very significant ionization which occurs. Since the water matrix would be highly ionized during pbar production, it would be possible for tritium produced from lithium to combine with ionized water so that tritiated water, readily measurable with standard laboratory techniques is collected. It was reasoned that this approach should work since tritium is similarly found in water which becomes activated due to accelerator operations. This approach was taken and did work as expected. There is however, no accounting for tritium gas which could have escaped from solution in the capped polyethylene bottles.

An array of aluminum tags was placed on the back side of the test stand to provide a basis for normalizing the activating particle fluence in the event the bottles were not evenly irradiated. The aluminum tags would be analyzed for sodium 22 which is produced as a spallation product on aluminum. The energy threshold for this reaction is quite high (approximately 1 GeV) compared to that for tritium production on lithium (thermal and low energies). A primary assumption made in this experiment is that the distribution of activating particle fluence is distributed similarly for high and low energies from beam centerline to about 230 milliradians. That is, the relationship of activating particle fluence with respect to distance from beam center for activation of aluminum is similar to that for activation of lithium, even though the magnitude of the distributions may not be similar. This assumption is made in order to extrapolate tritium production from the region where the bottles are to be placed to the lithium conductor. A better measurement could be in the future either with better tritium cross section data or with direct measurement of tritium produced in an actual lens.

An aluminum foil was also placed in the beam path for two purposes. First the activated foil could be used to make an auto-radiograph so that one could look for anomalous primary and secondary beam patterns downstream of the collection lens. Second, the activated foil could serve as a measure of secondary flux if

the total protons on target and the target interaction length were known over the period the apparatus was installed.

A sample of Kapton and an array of gold plated tungsten wires was placed on the test fixture behind the aluminum foil mentioned above. These materials were added for a test related for NUMI instrumentation and were not a part of the lithium irradiation experiment.

Finally, another set of metal samples and foils were placed on the test stand for another NUMI related test. The purpose was to understand activation and cooling times for various structural and shielding materials related to the NUMI target vault.

Digital photographs of the front, back, and side of the test fixture are included as Figure 1.

Experiment Run

The test fixture was installed on the bottom of the module used for the NUMI target test just downstream of the lithium lens module or about 61.3 cm downstream of the pbar target. The bottle side faced to the south or target side and the aluminum tag array was to the dump side of the target vault. The module was placed in the target vault on June 22, 2000. Beam was on target a total of 37.67 hours and the total intensity recorded by the Beam Budget Monitoring System for the period was $1.34E17$ protons. Table 1 includes a summary of the irradiation times and intensities delivered.

The module was removed from the target vault in the morning on June 29. The water and LiOH bottles were removed from the test fixture. The water and LiOH solutions were carefully transferred to clean new sample bottles which were transferred to the Activation Analysis Laboratory. The irradiated sample bottles were lightly browned and showed no evidence of leaking. However the bottle caps were very brittle; the top surface of one of them cracked off when it was tightened. The remaining caps were lightly tightened to prevent them from breaking. The bottles containing LiOH solutions were noted to contain white precipitates in their bottoms after the transfer which must have come out of solution perhaps as a result of the radiation exposure. These unexpected precipitates were to be dealt with later. The NUMI foils and metal samples were removed after the bottles and were handed over to the NUMI experimenters. Since the test fixture was fairly radioactive (about 2 R/hr at one foot), we decided to allow it to cool down before

removing the aluminum tags, aluminum foil, and Kapton/tungsten wire assembly. These materials were eventually removed eight days later on July 7.

Summary of irradiation times and proton intensity on target

Start Date	Start Time	End Date	End Time	Elapsed Time	Integrated Intensity
6/22	1220	6/23	0440	16.17 hours	4.96E16
6/27	0400	6/27	1430	10.5 hours	2.76E16
6/27	2130	6/28	0830	11 hours	5.67E16
			Totals	37.67 hours	1.34E17

Table 1

Data and Analysis

Aluminum Foil

The 3 mil, 4" diameter aluminum foil placed in the path of the beam was used to make an autoradiograph shown in Figure 2. Three positioning holes in the foil indicate the placement of the foil on the test fixture. The center of the hot spot is taken to be the primary beam center and is used as the center reference in the aluminum tag fit described later. A 2 cm diameter foil, an area corresponding to the central lithium conductor in the collection lens, was cut out of the 4 inch foil after locating the hot spot by autoradiograph. The foil was analyzed for Na22 and was reported to contain 1.64E5 pCi.

The pbar target thickness is about one interaction length. The total integrated intensity on target during the experimental run was 1.34E17 protons. Neglecting losses within the collection lens, the uninteracted primary beam which passed through the foil is approximately 4.93E16 protons. The spot size of the primary beam may be inferred from the burning/discoloration found in the Kapton foil which is shown in Figure 3. The spot is approximately 1 mm which agrees with pbar experience [7]. The cross section for Na

²² production in aluminum is approximately 10 mb* [8]. The activity due to activation of the primary beam may be calculated as follows:

$$A = \mathbf{s} \mathbf{f} N (1 - e^{-\mathbf{I} t_i}) \cdot (e^{-\mathbf{I} t_d}) \quad (1)$$

where:

$$\mathbf{s} = 10 \text{mb}$$

$$\mathbf{f} = \left(\frac{4.93 \text{E}16 \text{ protons}}{37.67 \text{ hours}} \frac{\text{hour}}{3600 \text{ s}} \frac{1}{(0.05 \text{ cm})^2 \mathbf{p}} \right) = 4.63 \text{E}13 \text{ cm}^{-2} \text{ s}^{-1}$$

$$N = (0.05 \text{ cm})^2 \mathbf{p} (3 \text{ mil}) \left(\frac{2.54 \text{ cm}}{1000 \text{ mil}} \right) \left(\frac{2.6989 \text{ g}}{\text{cm}^3} \right) \left(\frac{\text{mol}}{26.9815 \text{ g}} \right) \left(\frac{6.02252 \text{E}23}{\text{mol}} \right) = 3.61 \text{E}18 \text{ atoms}$$

$$t_i = 37.67 \text{ h}$$

Since the decay time is very short compared with half life of Na22, the last term is effectively 1.

Substituting these values into equation 1 with appropriate dimensional corrections,

$$A_p = 5.17 \text{E}14 \text{ pCi}$$

The activity due to secondaries is the difference between the total activity and that due to primaries or:

$$A_s = 1.64 \text{E}5 \text{ pCi} - 5.17 \text{E}14 \text{ pCi} = 1.12 \text{E}5 \text{ pCi}$$

Now the average flux due to secondaries on the remainder of the foil and coincidentally on the central lithium conductor can be determined by:

$$\mathbf{f} = \frac{A_s}{\mathbf{s} N (1 - e^{-\mathbf{I} t})}$$

* at 28 GeV, 9.8 mb ± 0.3 – J.B. Cummings, et. al. Physics Review 128, No. 5 (1962) 2392;
at 300 GeV, 9.4 mb ± 0.8 mb, S.B. Kaufman, Physics Review C19, No. 3 (1979) 962

where:

$$N = p(1cm)^2(3mil) \left(\frac{2.54cm}{1000mil} \right) \left(\frac{2.6989g}{cm^3} \right) \left(\frac{mol}{26.9815g} \right) \left(\frac{6.02252E23}{mol} \right) = 1.44E21atoms$$

Then:

$$f = \left[\frac{(1.12E5 pCi) \left(\frac{0.037d/s}{pCi} \right) \left(\frac{10^{27} mb}{cm^2} \right)}{(10mb)(1.44E21atoms) \left(1 - e^{-\frac{\ln 2}{2.602a} 37.67h} \right)} \right] = 2.53E11 cm^{-2} s^{-1}$$

The secondary flux result will be useful below in determining tritium production in the central lithium conductor.

The average secondary flux per proton incident on target is:

$$\frac{2.53E11 cm^{-2} s^{-1}}{1.34E17 protons} 37.67hours \frac{3600s}{h} = 0.25 cm^{-2} p^{-1}$$

Aluminum tags analysis and fit

The test fixture shown in figure 1 is a commercially made, 12"X24" aluminum plate with machined ¼-20 holes spaced horizontally and vertically on 1 inch centers. The aluminum tag array shown in Figure 1 was mapped out with respect to the test fixture plate and with the beam center as determined by the 3 mil aluminum foil described above. This mapping is shown in Figure 5. The aluminum tags were removed from the test fixture on July 7 and were counted on July 12 with a Bicon analyst. The detector probe was mounted in a fixture to establish fixed counting geometry with a distance of 0.75" between the end of the detector probe and the aluminum tags. The distance between the center of each tag on the fixture and the beam center was determined from the arrangement in Figure 5. A plot of the background corrected counting rates of each tag versus its distance from beam center is shown below in Chart 1. An equation included in the plot describes the fit and was used to determine the radius at 5000 cpm intervals from

15,000 to 95,000 cpm. Circles of the calculated radii were drawn in on the test fixture shown in Figure 5 and color was added to indicate how an aluminum tag count rate varies with distance.

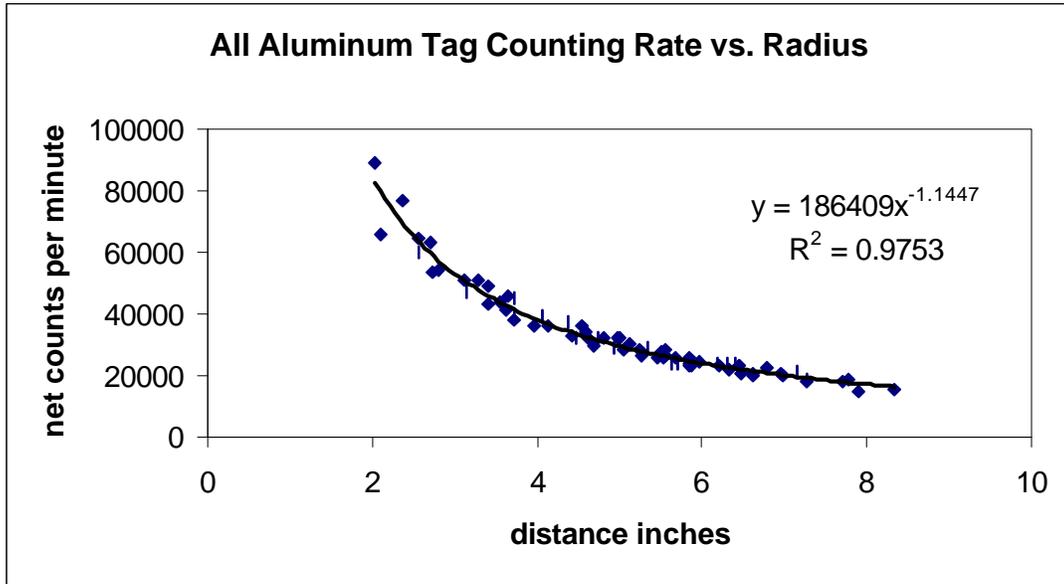


Chart 1

Three of the aluminum tags were submitted for Na22 analysis in order to determine Na22 activity versus counting rate. The flux is readily determined as was done in the foil analysis previously. With these results, the tag counting rate versus flux can be determined.

Tag Number	Background Corrected Count Rate (cpm)	Mass (g)	Activity (pCi/g)	Flux (cm ⁻² s ⁻¹)	Flux per tag cpm ((cm ⁻² s ⁻¹)/cpm)
5622	63008	2.9843	78,300	1.13E10	1.79E5
5625	26012	2.9929	33,800	4.89E9	1.88E5
5643	23642	2.9848	30,700	4.45E9	1.88E5
				Average	1.85E5

Table 2

Finally, an equation can be written which expresses the relationship of flux per incident proton as a function of radius at the longitudinal position of the test fixture:

$$\frac{f}{p}(R) = \left(\frac{1.85E5 \text{ cm}^{-2} \text{ s}^{-1}}{1.34E17 p} \right) (186,409) R^{-1.1447} = \frac{2.57E-7}{\text{cm}^2 \text{ s} \cdot p} R^{-1.1447}$$

where R is the number of inches from beam center to the position of interest.

The red rectangles indicated in Figure 5 represent the LiOH and water bottle locations on the test fixture.

Figure 4 shows the same array but with the contents of each bottle indicated. Each red rectangle was divided into 5 vertical slices representing equal fluid volumes. A weighted average of the aluminum tag counting rate was determined for each of the bottles and is shown in Table 3. Finally, the average flux over the individual bottles is obtained by multiplying the average tag count rate over the bottle volume by the factor derived in Table 2.

Bottle	Average Tag over bottle volume (cpm)	Average flux (cm ⁻² s ⁻¹)
Water 1	36401	6.73E9
Water 2	36830	6.81E9
Water 3	40679	7.53E9
Li6-95%	43705	8.09E9
Li7-97%	39908	7.38E9
Li7-99.55%	37766	6.99E9

Table 3

Water analysis for beryllium 7 and tritium – cross section determination

Water was transferred from the irradiated bottles to new bottles and then analyzed first for beryllium 7 and then for tritium. Tritium and beryllium 7 are expected to be produced as a spallation product from oxygen. Since deionized water was used, there are no other obvious significant production mechanisms. Equation 1 can be used once again, this time to derive production cross sections for tritium.

$$S_{H3} = \frac{A_{H3}}{fN_o(1 - e^{-I_{H3}t})}$$

Table 4 contains a summary of values used to determine the tritium production cross section on oxygen.

Bottle	Tritium (pCi/ml)	Volume (ml)	N _O	λ _{H3} (hours ⁻¹)	T (hours)	φ (cm ⁻² s ⁻¹)	σ _{H3} (mb)
Water 1	34,800	125	4.18E24	6.43E-6	37.67	6.73E9	23.6
Water 2	35,100	125	4.18E24	6.43E-6	37.67	6.81E9	23.5
Water 3	37,400	125	4.18E24	6.43E-6	37.67	7.53E9	22.7
						Average	23.3

Table 4

Similarly, the cross section for beryllium 7 on oxygen can be determined by:

$$S_{Be7} = \frac{A_{Be7}}{fN_o(1 - e^{-\lambda_{Be7}t})}$$

Table 5 contains a summary of values used to determine the beryllium 7 production cross section on oxygen.

Bottle	Be7 (pCi/ml)	Volume (ml)	N _O	λ _{Be7} (hours ⁻¹)	T (hours)	φ (cm ⁻² s ⁻¹)	σ _{Be7} (mb)
Water 1	561,000	125	4.18E24	5.42E-4	37.67	6.73E9	4.6
Water 2	550,000	125	4.18E24	5.42E-4	37.67	6.81E9	4.4
Water 3	602,000	125	4.18E24	5.42E-4	37.67	7.53E9	4.4
						Average	4.5

Table 5

LiOH solution analysis for beryllium 7 and tritium – production rate determination

LiOH solutions were also transferred from irradiated bottles to new clean bottles. It was noted during the transfer that some sort of precipitate remained in the irradiated bottles which was not present before irradiation. Meticulous records had been kept on masses and volumes of water and reagents used during LiOH solution preparation so that the number of moles of Li6, Li7, and oxygen exposed in the target vault

could be accounted for. The process became more difficult with the complication of the precipitate. This complication might have been avoided if non-saturated solutions of LiOH were used.

Each of the original LiOH samples were split into two parts, one containing the majority of the solution volume and a second consisting of a small quantity of slurry. The major solutions were first counted for beryllium 7. Next those solutions were neutralized with 0.8 normal HCl and a tritium concentration determination was made. The second part or slurry was treated by adding 100 ml of deionized water and neutralizing with 3.7 normal HCl. This step dissolved the precipitates leaving the bottles with a clean appearance. The second part was then analyzed for beryllium 7 and then for tritium. The total beryllium 7 and tritium activities were derived from the sum of the activities in the parts of the original samples. A set of bottle history flow charts provides the details and are included as Figures 6, 7, and 8. Table 6 provides a summary of the total beryllium 7 activity produced in the LiOH bottles. Table 7 provides a similar summary for tritium activity.

Solution	Be7 Specific activity in diluted slurry (pCi/ml)	Diluted slurry volume (ml)	Be7 Specific activity in major volume (pCi/ml)	Major volume (ml)	Total Be7 activity (pCi)	Normalized Be7 Specific Activity (pCi/ml)
Li6 – 95%	76,600	102	683,000	123.6	9.22E7	7.39E5
Li7 – 97%	8,210	106	611,000	123.5	7.63E7	6.12E5
Li7 – 99.55%	11,500	101	626,000	122.7	7.8E7	6.25E5

Table 6

Solution	H3 Specific activity in slurry (pCi/ml)	Slurry volume (ml)	H3 Specific activity in major volume (pCi/ml)	Major volume (ml)	Total H3 activity (pCi)	Normalized H3 Specific Activity (pCi/ml)
Li6 – 95%	7,970,000	1.09	987,000	123.6	1.31E8	1.05E6
Li7 – 97%	1,340,000	1.2	169,000	123.5	2.25E7	1.80E5
Li7 – 99.55%	66,900	2.16	8,510	122.7	1.19E6 ¹	9.53E3

Table 7

At this point, the remaining unknown quantities are the cross sections for tritium and beryllium 7 production on Li6 and Li7 and the activating flux as a function of energy. For purposes of this experiment, it is assumed that:

$$f_{Na22_{AL}}(E) = K f_{H3_{Li}}(E)$$

where K is a constant .

Equation 1 can be used to write the activation equation for each of the LiOH solution bottles as follows:

$$\left[N_{Li6} K_{Li6} s_{Ht_{Li6}} + N_{Li7} K_{Li7} s_{Ht_{Li7}} + N_O s_{Ht_O} \right] f(1 - e^{-It}) = A_{Li6-95\%}$$

$$\left[N_{Li6} K_{Li6} s_{Ht_{Li6}} + N_{Li7} K_{Li7} s_{Ht_{Li7}} + N_O s_{Ht_O} \right] f(1 - e^{-It}) = A_{Li7-97\%}$$

These equations can be simplified to:

$$mols_{Li6} K_{Li6} s_{Ht_{Li6}} + mols_{Li7} K_{Li7} s_{Ht_{Li7}} = \frac{A_{Li6-95\%}}{N_A f(1 - e^{-It})} - mols_O s_{Ht_O}$$

$$mols_{Li6} K_{Li6} s_{Ht_{Li6}} + mols_{Li7} K_{Li7} s_{Ht_{Li7}} = \frac{A_{Li7-97\%}}{N_A f(1 - e^{-It})} - mols_O s_{Ht_O}$$

where N_A is Avogadro number.

¹ This result is lower than expected.

The values to be substituted into these equations are included in Table 8.

Bottle	mols O	σ_{HtO} (mb)	mols Li6	mols Li7	ϕ (cm ⁻² s ⁻¹)	(1-e ^{-λt})	Total tritium activity (pCi)
Li6-95%	7.534	23.3	0.572325	0.030123	8.09E+09	2.419E-4	1.31E8
Li7-97%	7.384	23.3	0.0178013	0.575573	7.38E+09	2.419E-4	2.25E7
Li7-99.55%	7.393	23.3	0.590609	0.002699	6.99E+09	2.419E-4	1.19E6

Table 8

The sample result for tritium in the Li7-99.55% bottle was less than predicted for tritium on oxygen.

Inserting known values and simplifying yields:

$$0.572325K_{\text{Li6}}\mathbf{s}_{\text{HtLi6}} + 0.0301226K_{\text{Li7}}\mathbf{s}_{\text{HtLi7}} = 3937mb$$

$$0.0178013K_{\text{Li6}}\mathbf{s}_{\text{HtLi6}} + 0.575573K_{\text{Li7}}\mathbf{s}_{\text{HtLi7}} = 602mb$$

The solution yields:

$$K_{\text{Li6}}\mathbf{s}_{\text{HtLi6}} = 6835mb$$

$$K_{\text{Li7}}\mathbf{s}_{\text{HtLi7}} = 835mb$$

The same process is used to determine cross sections for Be7 production on Li6 and Li7 with the set of equations:

$$mols_{\text{Li6}}K_{\text{Li6}}\mathbf{s}_{\text{Be7Li6}} + mols_{\text{Li7}}K_{\text{Li7}}\mathbf{s}_{\text{Be7Li7}} = \frac{A_{\text{Li6-95\%}}}{N_A \mathbf{f}(1 - e^{-It})} - mols_{\text{O}}\mathbf{s}_{\text{HtO}}$$

$$mols_{\text{Li6}}K_{\text{Li6}}\mathbf{s}_{\text{Be7Li6}} + mols_{\text{Li7}}K_{\text{Li7}}\mathbf{s}_{\text{Be7Li7}} = \frac{A_{\text{Li7-97\%}}}{N_A \mathbf{f}(1 - e^{-It})} - mols_{\text{O}}\mathbf{s}_{\text{HtO}}$$

The values to be substituted into these equations are included in Table 9.

Bottle	mols O	σ_{Be7O} (mb)	mols Li6	mols Li7	ϕ (cm ⁻² s ⁻¹)	(1-e ^{-λt})	Total Be7 activity (pCi)
Li6-95%	7.534	4.5	0.572325	0.030123	8.09E+09	2.021E-2	9.22E7
Li7-97%	7.384	4.5	0.0178013	0.575573	7.38E+09	2.021E-2	7.63E7
Li7-99.55%	7.393	4.5	0.002699	0.590609	6.99E+09	2.021E-2	7.8E7

Table 9

Inserting known values and simplifying yields:

$$0.572325K_{Li6}S_{Be7_{Li6}} + 0.0301226K_{Li7}S_{Be7_{Li7}} = 0.742mb \quad \text{Li6-95\%}$$

$$0.0178013K_{Li6}S_{Be7_{Li6}} + 0.575573K_{Li7}S_{Be7_{Li7}} = -1.8mb \quad \text{Li7-97\%}$$

$$0.002699K_{Li6}S_{Be7_{Li6}} + 0.590609K_{Li7}S_{Be7_{Li7}} = 0.653mb \quad \text{Li7-99.55\%}$$

The equation for the Li7-97% bottles yields a negative result. This is evidence that the production cross section for beryllium 7 on lithium is near the detection limit of this experiment. Proceeding, perhaps imprudently, using the first and third relationships yields:

$$KS_{Be7_{Li6}} = 1.24mb$$

$$KS_{Be7_{Li7}} = 1.1mb$$

Extrapolation to lithium lens conductor

Previously, it was determined that the secondary flux per proton over the central conductor of the lithium lens was 0.25 cm⁻²p⁻¹ and about 1/e of the primary beam is incident of the lithium lens. The lens central conductor has a radius of 1 cm and a length of 15.6 cm. Some desirable operating parameters for lithium lens operation in collider run II are beam intensity of 5E12 protons per pulse every 2 seconds for a total of

10 million pulses for a total operating period of about 5600 hours. The total tritium produced over the lifetime of such a lens can be derived using the data in Table 10 and, once again, the equation:

$$A = sfN(1 - e^{-It_i}) \cdot (e^{-It_d})$$

Table 10 contains pertinent values used to make the estimate assuming the use of natural lithium (92.5% Li7, 7.5% Li6) in the lens conductor. For each isotope of lithium, there is an entry for tritium production due to secondaries, and for completeness, for primaries.

isotope	N	Kσ (mb)	φ/p (cm ⁻² p ⁻¹)	Irradiation time (hours)	Intensity (ppp)	Cycle time (s)	φ (cm ⁻² s ⁻¹)	Tritium activity (pCi)
Li6	1.7E23	6835	0.25	5600	5E12	2	8.3E11	9.2E11
Li6	4.26E20	6835	1/e	5600	5E12	2	1.56E14	4.4E11
Li7	2.1E24	835	0.25	5600	5E12	2	8.3E11	1.4E12
Li7	5.26E21	835	1/e	5600	5E12	2	1.56E14	6.5E11
							Total	3.4E12

Table 10

Based on this analysis, the total tritium inventory of an expended lens due to activation by primary and secondary beam incident over the desired operating life of a collection lens is about 3.4 Ci.

The inventory of Be7 can be estimated similarly. Table 11 contains pertinent values to make the estimate, again assuming natural Li is used in the lens conductor.

isotope	N	Kσ (mb)	φ/p (cm ⁻² p ⁻¹)	Irradiation time (hours)	Intensity (ppp)	Cycle time (s)	φ (cm ⁻² s ⁻¹)	Beryllium 7 activity (pCi)
Li6	1.7E23	1.2	0.25	5600	5E12	2	8.3E11	4.4E9
Li6	4.26E20	1.2	1/e	5600	5E12	2	1.56E14	2.1E9
Li7	2.1E24	1.1	0.25	5600	5E12	2	8.3E11	4.9E10
Li7	5.26E21	1.1	1/e	5600	5E12	2	1.56E14	2.3E10
							Total	7.9E10

Table 11

Based on this analysis, the total beryllium 7 inventory of an expended lens due to activation by primary and secondary beam incident over the desired operating life of a collection lens is about 79 mCi.

Gas production

The quantity of tritium calculated in Curies in the preceding section can be converted to liters as follows:

$$A = \lambda N$$

where:

A is Activity

λ is the decay constant

N is total number of tritium atoms.

Substituting and applying the appropriate dimensional corrections:

$$N = \left(\frac{3.4 \text{ Ci}}{\ln 2 / 12.323 \text{ a}} \right) \left(\frac{365 \text{ d}}{\text{a}} \frac{24 \text{ h}}{\text{d}} \frac{3600 \text{ s}}{\text{h}} \right) \left(\frac{3.7 \text{ E}10 \text{ d/s}}{\text{Ci}} \right) \left(\frac{\text{atoms}}{\text{d}} \right) \left(\frac{\text{mol}}{6.022 \text{ E}23 \text{ atoms}} \right) \left(\frac{22.4 \text{ liters}}{\text{mol}} \right) = 0.0026 \text{ liters}$$

The calculation implies that tritium exists as a gas within the lithium conductor. It is possible however, that the tritium exists in a form such as lithium hydride. The production of other non-radioactive gas (simple hydrogen, deuterium, helium 3 and helium4) is also expected and should be considered. If the production rates of these gases can be established relative to the production of tritium, an estimate of the total gas production can be made.

Conclusions

The production of tritium and beryllium 7 has been measured in the target vault environment. The production rate of these isotopes has been extrapolated to arrive at a production rate with the lithium conductor within the collection lens body. From these results it is apparant that tritium production is about 8 times more likely with Li6 than with Li7.

Some sources of error to be concerned about in this measurement.

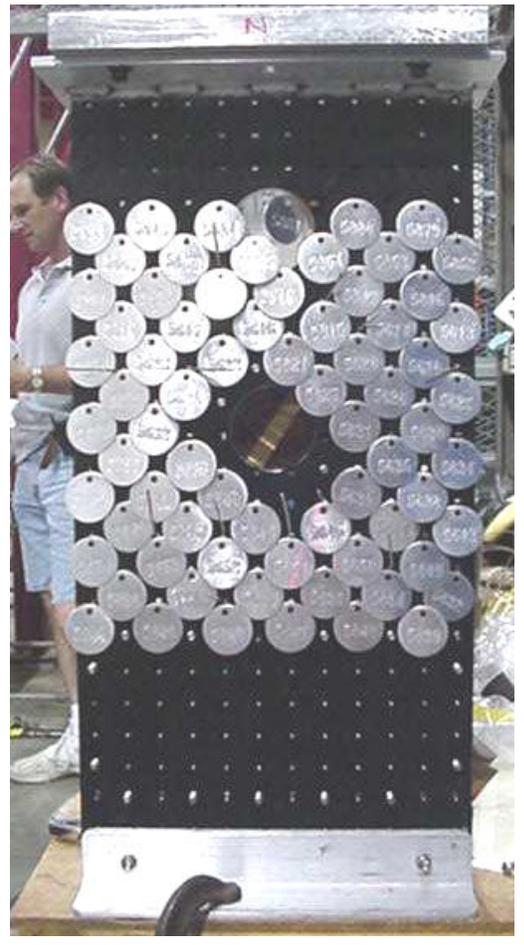
1. The recombination of tritium with ionized water is the basis for capturing and measuring tritium production. There is no accounting for tritium gas which may be produced and released from the solution. The low tritium result for the 99.55% Li7 solution is of special concern. The total tritium measured in this solution was less than that found in the demineralized water samples and has not been accounted for and is an indication that the error may be very significant.
2. It is assumed that the high energy activating fluence for production of sodium 22 on aluminum is proportional to the medium to low energy activating fluence for production of tritium from isotopes of lithium. While this is a reasonable assumption for predicting production of tritium on oxygen in water, it may not be a reasonable assumption for production of tritium on isotopes of lithium at low to medium energies.

References

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4. Run II Parameters, Handbook and Operation <http://www-bd.fnal.gov/runII/index.html>
5. Aldrich, 1001 West Saint Paul Avenue, Milwaukee, WI
6. NUKEM Inc. 39 Old Ridgebury Rd, Section B-1, Kevin Alldred Danbury CT 06810
7. Private communication with Jim Morgan

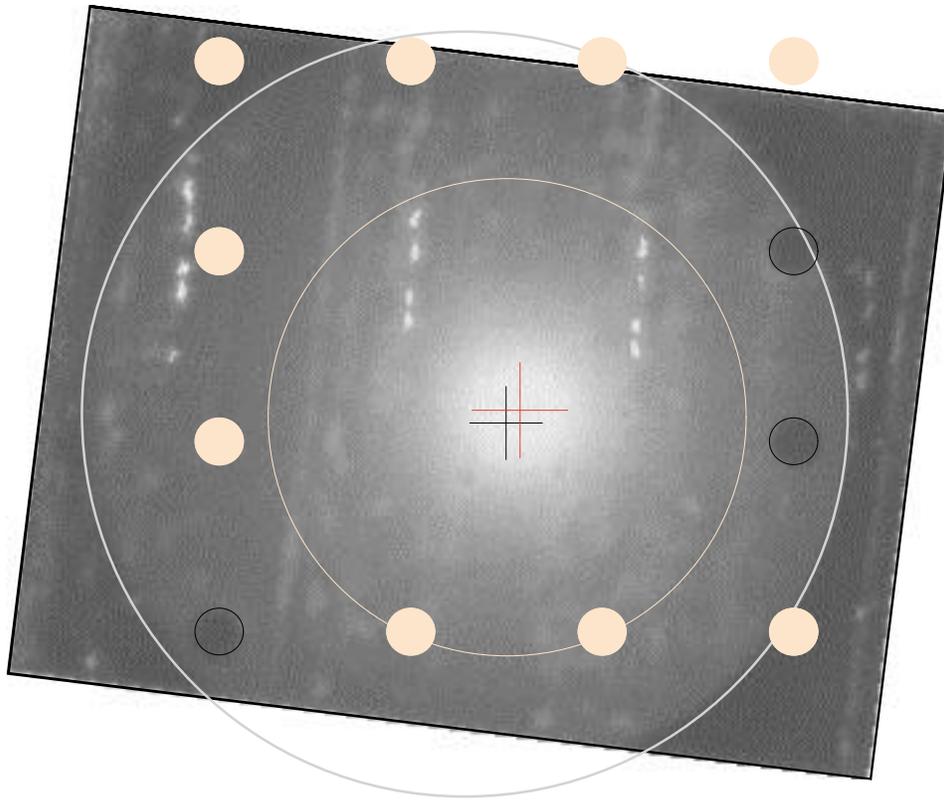
8. Private communication with Steve Benesch

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Test fixture front side	Test fixture side view	Test Fixture back side
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Figure 1



Beam into paper



foil orientation holes on bolt pattern



indicates holes in plate



foil outline



fixture hole centerline



beam center

Figure 2. Autoradiograph of 3 mil aluminum foil, 5 day exposure, full scale

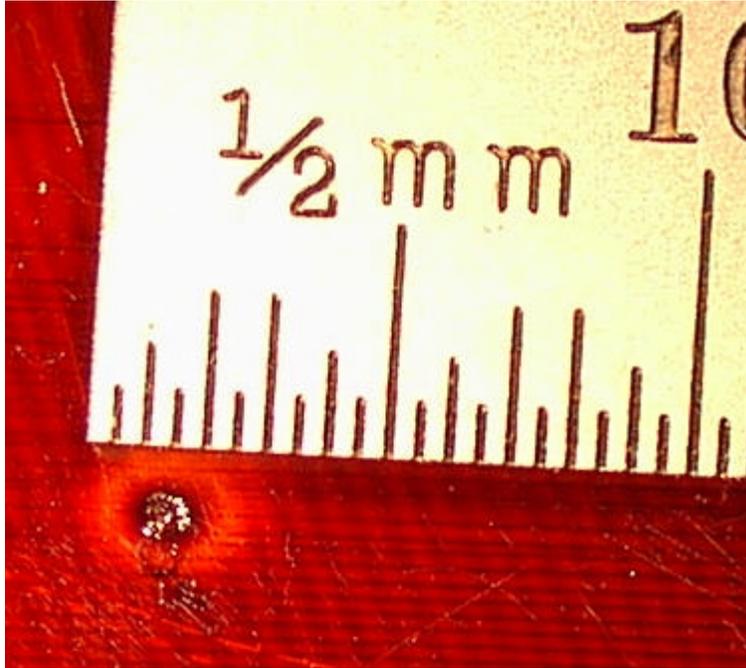


Figure 3 Discoloration attributed to uninteracted primary beam

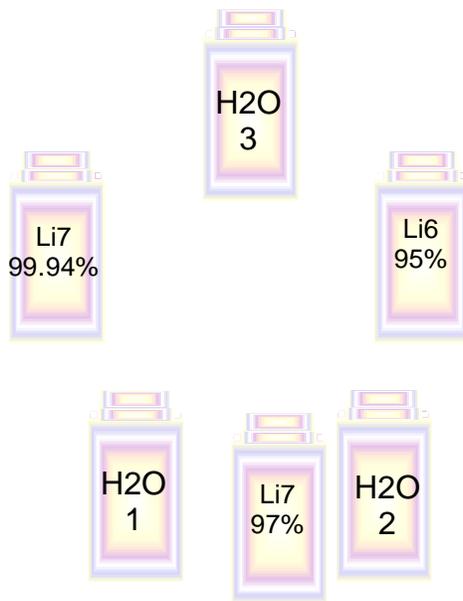
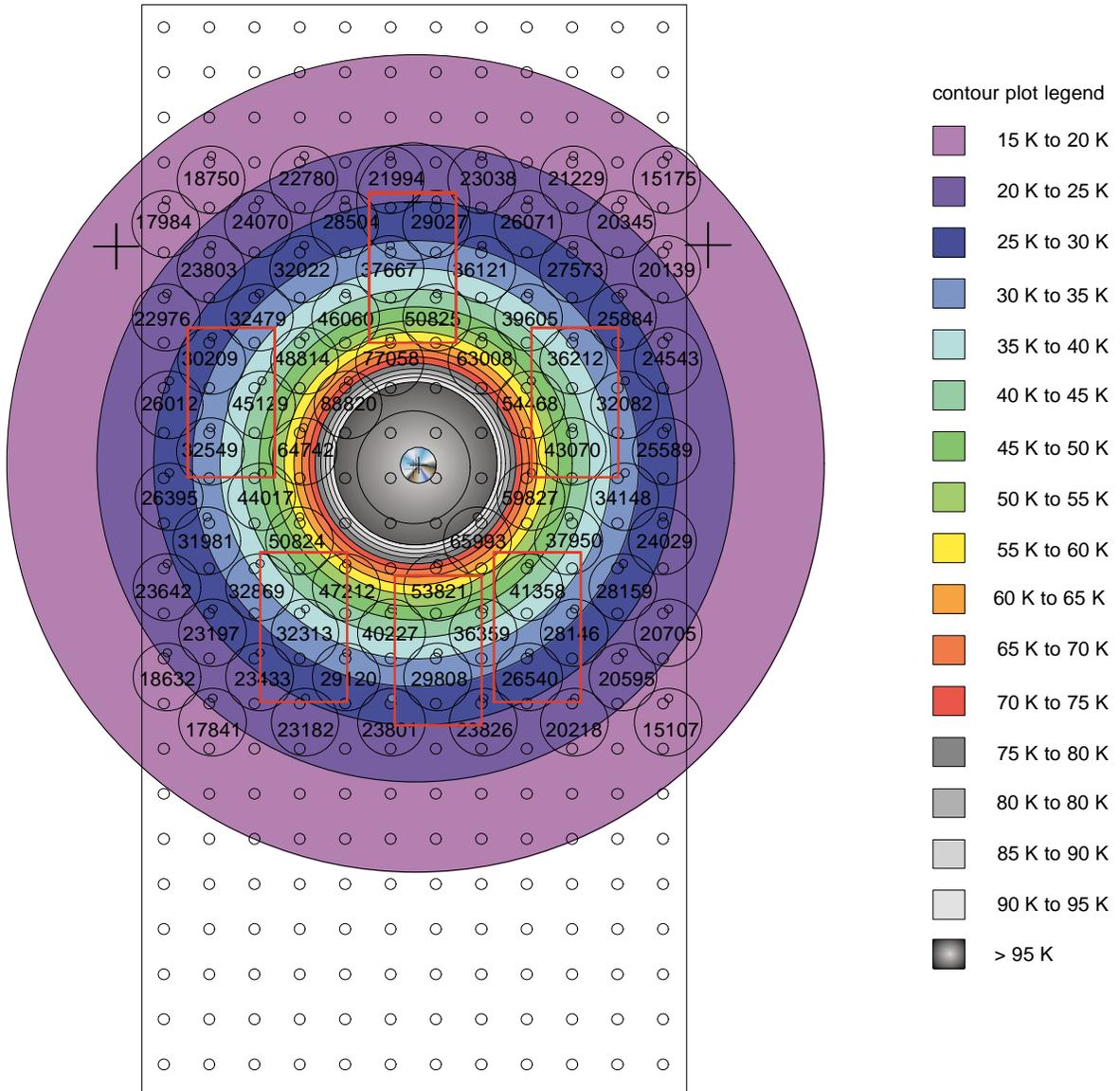


Figure 4 Position of Bottles by Contents



NOTE: The cross hair in the tag layer represents the beam spot center. It does not represent the center of the plate hole. The shiny tag representing the 3 mil Al foil is centered on the the spot center and not on the center cross hair of the plate. Normalization is made relative the the center of the beam spot.



Figure 5 Aluminum Tag Layout and Contour Plot

Li6

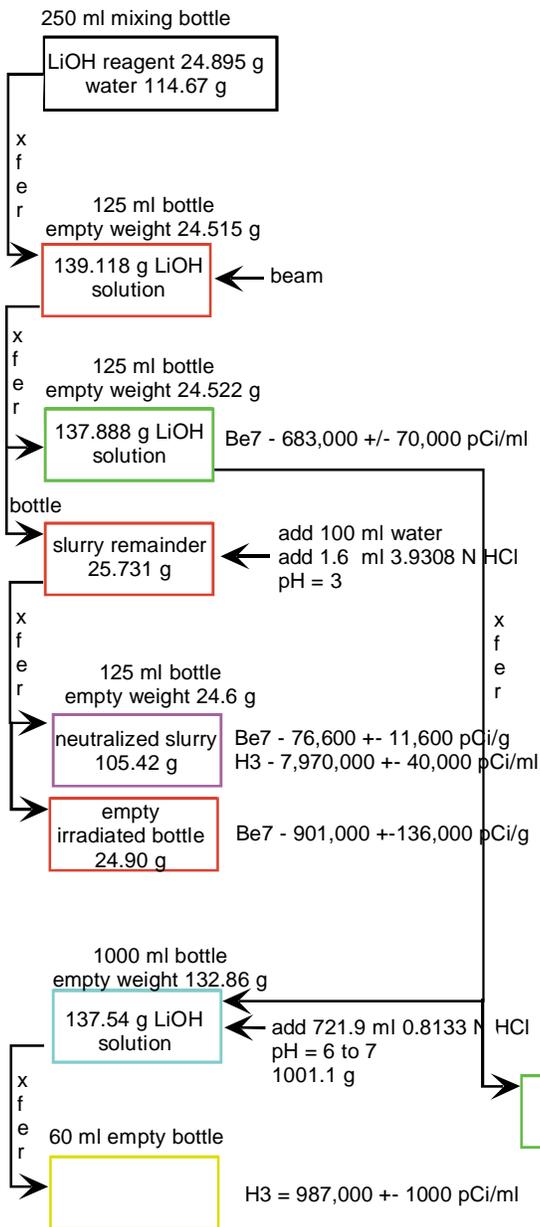


Figure 6 Li6-95% Bottle History

Li7 - 97%

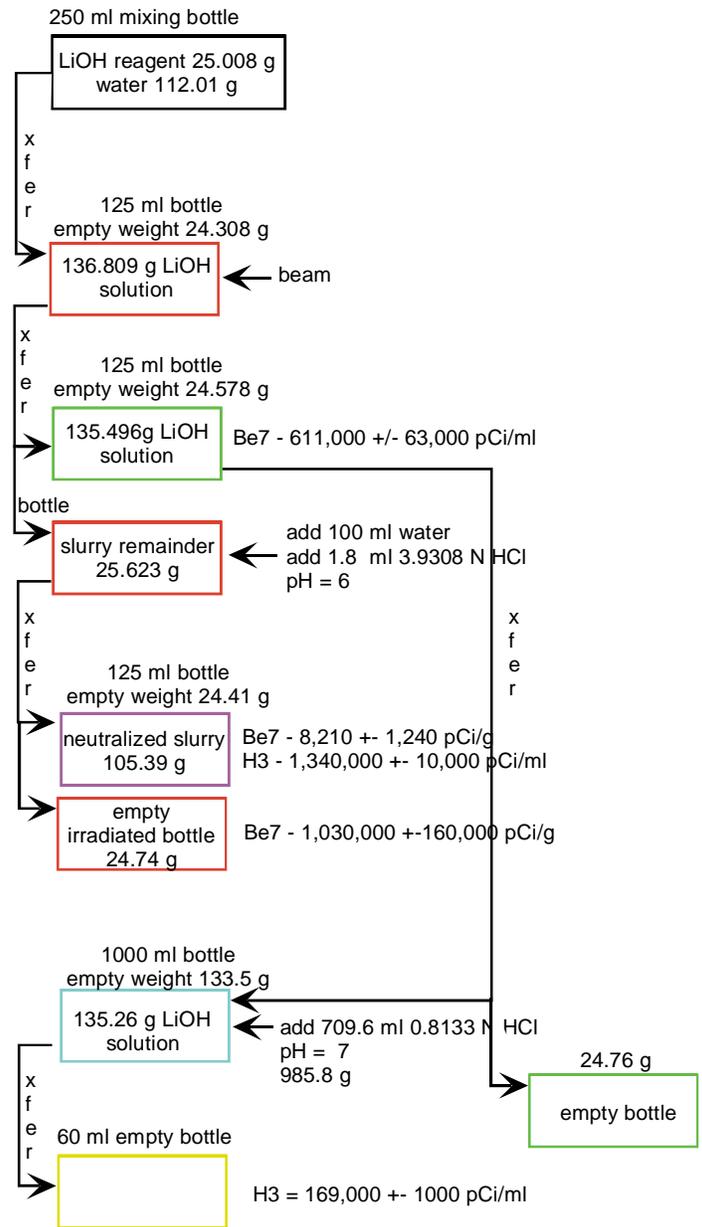


Figure 7 Li7 - 97% Bottle History

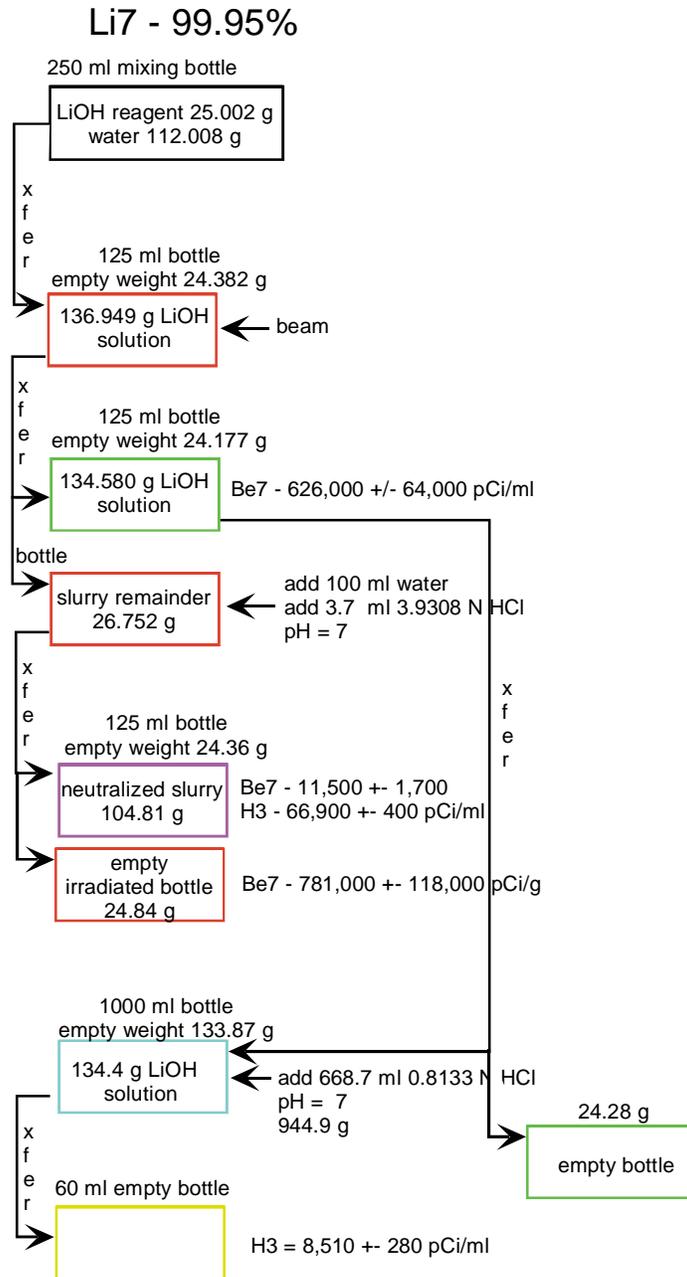


Figure 8 Li7 - 99.55% Bottle History