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# Assessment of the $^{3}$H and $^{7}$Be generation in the IFMIF lithium loop

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## Abstract

A complete evaluation of the $^{7}$Be and tritium inventory induced in the IFMIF lithium loop by deuterons and neutrons was performed on the basis of 3D Monte Carlo calculations with the M$^{C}$DeLicious code and evaluated d-Li and n-Li cross-section data. The associated reaction cross-sections and thick lithium target yields were checked against available experimental data. The IFMIF calculations showed that the deuteron beam will produce 1.5 g of $^{7}$Be and 6 g of $^{3}$H per full power year in the lithium jet. The tritium generation in the whole lithium loop due to neutron induced reactions is at a rate of 1.5 g/fpy. The radio-active decay results in an equilibrium concentration 0.3 mg of $^{7}$Be and 50 mg of $^{3}$H per 1 kg of circulating lithium if no radioactive products are removed from the loop.

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## 1. Introduction

In the International Fusion Material Irradiation Facility (IFMIF), high energy neutrons will be produced by 40 MeV deuterons striking a liquid lithium jet target [1,2]. The liquid lithium will circulate in a loop which includes the jet, pipes and a quench tank with a total amount of 1.2 tons of lithium. Tritium and beryllium-7 will be produced in the target as result of deuteron reactions with Li nuclei. Neutrons generated in the target, in turn, will produce tritium in the whole lithium loop by Li(n,$x$)T reactions. The radioactive $^{7}$Be and T inventory will be uniformly distributed over the whole lithium loop. For safety reasons, the radioactive inventory of the Li loop during IFMIF operation and shutdown periods must be well known. Recent measurements indicated that the production of $^{7}$Be previously was underestimated by a factor 3–4 at 40 MeV deuteron energy. The total tritium inventory in the loop so far was not considered due to lacking n-Li reaction cross-sections above 20 MeV.

This work presents a complete evaluation of the $^{7}$Be and $^{3}$H inventory induced in the IFMIF Li loop by deuterons and neutrons using recently evaluated $^{6,7}$Li cross-section data [3]. The deuteron activation processes are described by means of Monte Carlo calculations with the M$^{C}$DeLicious code [4], which is capable of simulating the deuteron beam profile, the deuteron slowing down in lithium as well as the generation of neutrons, photons and radioactive products caused by d-Li reactions. Its capability to predict the $^{7}$Be and $^{3}$H generation was checked against measured reactions cross-sections and thick lithium target yields.

## 2. IFMIF design and methods of nuclear activation assessment in the Li loop

A schematic drawing of the IFMIF test cell is shown in Fig. 1. A dual beam of deuterons, each of 125 mA current, 40 MeV energy and 20×5 cm$^{2}$ footprint, impinges onto the open surface of a lithium jet. The deuterons are slowed down in the jet, deposit their whole energy and generate neutrons through the various Li(d,$x$n) reactions. The nuclear interaction of the

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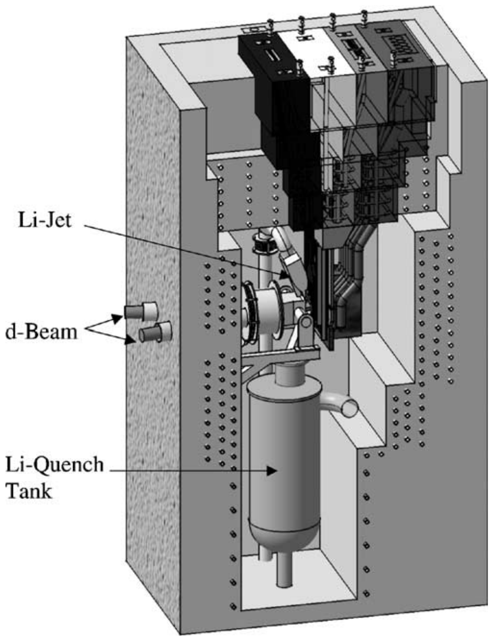

Fig. 1. Lay out of the IFMIF test cell with Li loop.

deuterons with the Li isotopes will also produce the following unstable nuclei: (i) $^7$Be, half life $T_{1/2} = 53.1$ days, decaying via electron capture (EC) to the stable $^7$Li with emission of 478 keV $\gamma$-rays; (ii) $^3$H, half life $T_{1/2} = 12.3$ years, decaying to the stable $^3$He with emission of $\beta^-$ particles of 5.7 keV average energy. Tritium will be also produced by neutron induced reactions in the whole loop of the IFMIF test cell.

For the assessment of the $^7$Be and T generation the recently developed Monte Carlo code M$^C$DeLicious [4] was applied. M$^C$DeLicious is an extension to MCNP-4C [5] with the capability of simulating the generation of neutrons, tritons, $\gamma$-rays and other d-Li reaction products on the basis of evaluated Li(d,$x$n) data taking into account the spatial configuration of the deuteron beams and the deuteron slowing down in the lithium target. Use is made of tabulated cross-sections evaluated for the deuteron interaction with $^{6,7}$Li isotopes up to 50 MeV [3]. The generated tritons and $^7$Be nuclei are scored to assess their production rates while the generated neutrons and $\gamma$-rays with the associated energy-angle distributions are further used in the transport simulation by the MCNP-4C code. For the assessment of the tritium production from the n-Li interactions the track length estimator of the neutron flux was used. The required n-Li tritium response functions were taken from the 50 MeV data evaluations for $\mathrm{n} + {}^{6,7}$Li [3]. The M$^C$DeLicious approach has been validated to ensure a good representation of the neutron yield spectra from thick lithium targets and has been applied for the neutronic characterisation of IFMIF as well [4,6–8].

## 3. $^7$Be and $^3$H production cross-sections for the deuteron and neutron interaction with lithium

The cross-sections for the deuteron interaction with lithium isotopes producing $^7$Be are shown in Fig. 2. The data for $^7$Li(d, 2n)$^7$Be reaction measured up to 13 MeV in two experiments [9,10] disagree with each other by about 40%. The INPE-FZK evaluation [3] for this reaction performed in 1997 agrees with the data of Guzhovskij et al. [9]. However, recent measurements of Baba et al. [11] confirm the Vysotskij data [10], thus indicating the necessity for increasing the evaluated cross-section of the $^7$Li(d, 2n)$^7$Be reaction. The cross-section for the $^6$Li(d,2n)$^7$Be reaction was measured in [9,12]. Since there is no evaluation for this reaction, an eye-guide curve through the experimental data was used as shown in Fig. 2. The cross-section of the tritium producing reaction Li(d,$x$)T was measured only below 4 MeV [13]. As Fig. 3 shows, the INPE-FZK evaluation agrees with these data.

In addition to the reaction cross-sections, the $^7$Be and T yields for thick lithium targets (TTY) bombarded by deuterons were also measured in a series of experiments [11,14–17]. These can be used for validation analyses. Fig. 4 shows that the results of the present calculations generally agree with TTY experimental data. The recent measurements of Baba et al. [11] and Möllendorff et al. [17] at 40 MeV deuteron energy are underestimated by ≈15%. This slight underestimation confirms the necessity for increasing the $^7$Li(d, 2n)$^7$Be reaction cross-sections below 40 MeV. For the comparison, the IRAC model calculations [18] for the beryllium-7 inventory in lithium is shown in the same figure. It is seen that the IRAC model does not account for the $^6$Li(d, n)$^7$Be reaction, which is the only contribution below 7 MeV, and underestimates the $^7$Be inventory by factor of 3 at 40 MeV deuteron energy.

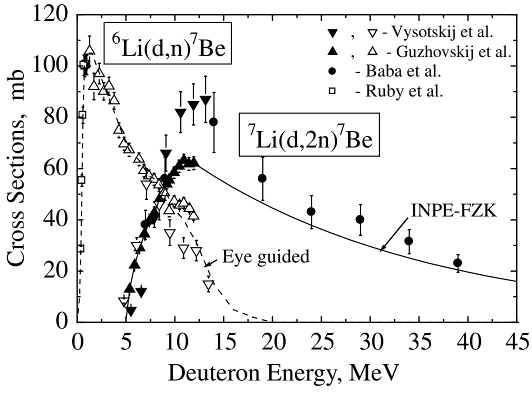

Fig. 2. Cross-sections for $^6$Li(d, n)$^7$Be and $^7$Li(d, 2n)$^7$Be reactions. Experimental data: (△, ▲) [9], (▽, ▼) [10], (●) [11]; (□) [12]. Evaluation: (–––) INPE-FZK file [3]; (- - -) eye-guided.

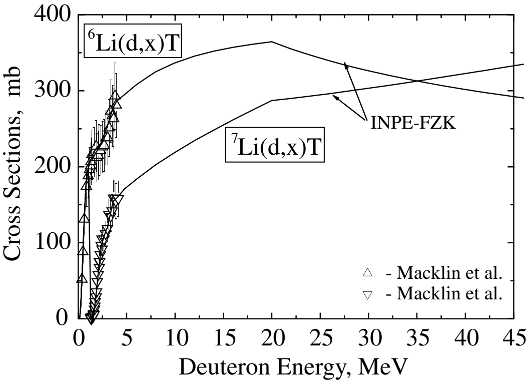

Fig. 3. Cross-sections for $^{6}\mathrm{Li}(d,x)^{3}\mathrm{H}$ and $^{7}\mathrm{Li}(d,x)^{3}\mathrm{H}$ reactions. Experimental data: (△, ▽) [13]. Evaluation: (– – –) INPE-FZK file [3].

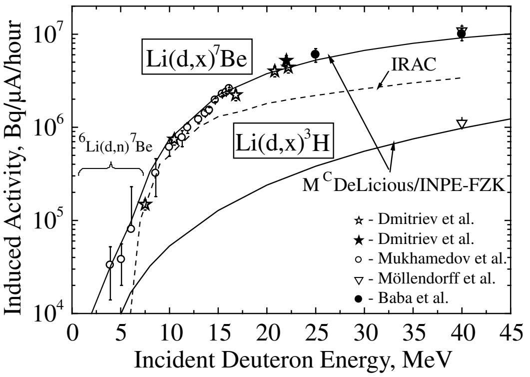

Fig. 4. $^7$Be and T inventory in the thick lithium target bombarded by deuterons. Experimental data: (☆) [14]; (★) [15]; (○) [16]; (●) [11]; (▽) [17]. Calculations: (– – –) M$^C$DeLicious with INPE-FZK file; (- - -) IRAC code [18].

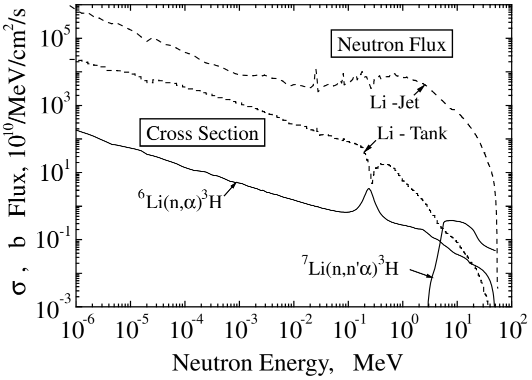

Fig. 5. Cross-sections for $^{6}\mathrm{Li}(n,x)^{3}\mathrm{H}$ and $^{7}\mathrm{Li}(n,x)^{3}\mathrm{H}$ reactions from INPE-FZK evaluation (– – –) and neutron spectral fluxes averaged over the volumes of the lithium jet and quench tank as calculated by the M$^C$DeLicious code (- - -).

The tritium production cross-sections for the neutron induced reactions on lithium isotopes are shown in Fig. 5. These cross-sections, especially the $^{6}\mathrm{Li}(n,\alpha)^{3}\mathrm{H}$ reaction, were frequently measured and are well reproduced by the INPE-FZK evaluation below 20 MeV. Above this energy there are still no experimental data available.

## 4. Assessment of $^7$Be and $^3$H inventories in the IFMIF lithium loop

A detailed 3-d geometrical model was developed to represent the configuration of the lithium loop and the IFMIF test cell. The loop was considered as consisting of two parts: a jet irradiated by the deuteron beam (rectangular box of $24\times2.5\times36$ cm$^3$; 1 kg lithium) and a quench tank (cylinder ∅ 70 cm × 80 cm, 1200 kg lithium). The neutronics calculations have shown that the tritium inventory in other parts of the lithium loop is negligible. The loop was filled with liquid lithium at a density of 0.512 g/cm$^3$ and natural isotope composition. The test cell was represented by the lithium jet back plate, test modules, concrete walls (Fig. 1), steel liner and an argon gas filling the test cell volume at 0.1 Pa [8].

For the neutron transport calculations the neutron interaction cross-sections with $^{6,7}$Li evaluated up to 50 MeV [3] were used, for other structural elements the high energy data were taken from the LA-150 [19] or the INPE-FZK-50 [20] libraries. The calculated neutron fluxes averaged over the lithium jet and quench tank volumes are shown in Fig. 5 and Table 1. It is seen that the neutron flux in the jet is 3 orders of magnitude higher than in the quench tank and the spectral distribution is harder (10% of the neutrons have energy greater than 20 MeV). This results in tritium production ratios $^{6}\mathrm{Li}(n,\alpha)^{3}\mathrm{H}/^{7}\mathrm{Li}(n,n'\alpha)^{3}\mathrm{H}$ of 70/30 and 95/5 for the lithium jet and the quench tank, respectively.

The $^7$Be and T production rates calculated for the lithium loop during IFMIF full power operation (40 MeV at 250 mA) are listed in Table 1. It is seen that 1.5 g of beryllium-7 and 6.0 g of tritium will be generated by the deuteron beam interaction with the lithium jet. The tritium inventory caused by the n-Li reactions in the loop will amount to 1.5 g/fpy, the dominant generation source being the quench tank. The total radioactive inventory ($^7$Be and T) amounts to 9 g per full power year.

The assessment of $^7$Be and T concentrations in the lithium loop during steady IFMIF operation was performed by taking into account the radionuclide production rate (data from Table 1) and the radioactive natural decay. In this calculation a possible removal of these radio-nuclides from the lithium loop by a purification system was not considered, although a cold trap and two hot traps are planned for control of $^7$Be and T. The calculated specific inventories are shown in Fig. 6. It

Table 1
IFMIF lithium loop parameters, neutron fluxes, nuclear reactions and radionuclide inventories during IFMIF full power operation (40 MeV at 250 mA deuteron beam)

| Li loop component | Mass (kg) | n-Flux ($n/cm^2/s$) | Nuclear reaction | Radio nuclide | Inventory rate (gram/fpy) |
|---|---|---|---|---|---|
| Li jet (close to d-beam) | ≈1 | | d + Li | $^7Be$ | 1.5 |
| | | | d + Li | $^3H$ | 6.0 |
| | | $3.1\times10^{14}$ | n + Li | $^3H$ | 0.4 |
| Li quench tank | ≈1200 | $4.1\times10^{11}$ | n + Li | $^3H$ | 1.1 |
| Sub-total (only $^3H$) | | | | | **7.5** |
| Total ($^3H+{}^7Be$) | | | | | **9.0** |

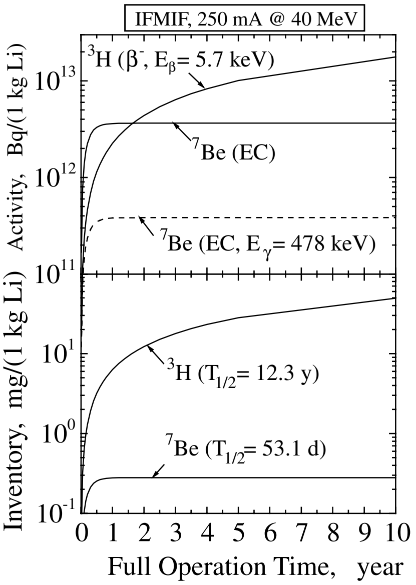

Fig. 6. Specific tritium and beryllium-7 inventories (bottom) and radio activities (top) for the IFMIF lithium loop versus operation time as calculated by the M$^C$DeLicious code.

is noted that $^7Be$ concentration reaches an equilibrium value of 0.3 mg per 1 kg lithium in about 1 year, whereas the amount of T will dominate and increase up to 50 mg/kg in 10 years. The radioactivity of lithium circulating in the loop will be determined by the decay of $^7Be$ at a rate of $4\times10^{12}$ Bq/1 kg. Since only 10.5% of $^7Be$ disintegrations followed by emission of 478 keV γ-rays, the γ-rays activity of lithium will be $4\times10^{11}$ Bq/1 kg. The β-activity of the lithium results from the tritium decay and can reach $2\times10^{13}$ Bq/1 kg in 10 years of IFMIF operation.

## 5. Conclusion

A complete evaluation of the $^7Be$ and tritium inventory induced in the IFMIF lithium loop by deuterons and neutrons was performed on the basis of 3D Monte Carlo calculations with the M$^C$DeLicious code and evaluated 50 MeV d-Li and n-Li cross-section data. Checks against measured microscopic cross-sections and thick lithium target data were performed to validate the $^7Be$ and tritium inventory calculations for IFMIF.

The assessment of the lithium loop activation during IFMIF operation has shown that the deuteron beam will produce 1.5 g of $^7Be$ and 6 g of $^3H$ per full power year in the Li-jet. Additionally 1.5 g/fpy of tritium will be generated in the whole loop by neutron induced reactions. Taking into account the radio-active decay results in a equilibrium concentration 0.3 mg of $^7Be$ and 50 mg of $^3H$ per 1 kg of circulating lithium. This corresponds to a specific γ-activity of $4\times10^{11}$ and a $\beta^-$-activity up to $2\times10^{13}$ Bq per kg Li if no radioactive products are removed from the loop.

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