Fluka simulations for DY 2018 run

- Overview
- Neutron capture
- Simulations
- Suggestions
- Conclusions
Neutrons capture materials possible candidates

The neutrons absorber candidate are:

- **$^6$Li**
  - Cross section at 2200 m/s: 940 barn
  - Natural abundance: 7.5%
  - $^6$Li + n → t (2.05 MeV) + $\alpha$ (2.73 MeV)

- **$^{10}$B**
  - Cross section at 2200 m/s: 3839 barn
  - Natural abundance: 19.9%
  - $^{10}$B + n → $^7$Li (0.84 MeV) + $\alpha$ (1.47 MeV)… (93.7 %)
  - $^7$Li → $^7$Li (1.02 MeV) + $\gamma$ (1.78 MeV)
  - $^{10}$B + n → $^7$Li (1.02 MeV) + $\alpha$ (1.78 MeV)… (6.3 %)

- **$^{113}$Cd**
  - Cross section at 2200 m/s: 20600 barn
  - Natural abundance: 12.2%
  - Many with $\gamma$ and $\alpha$ emission

- **$^{155}$Gn and $^{157}$Gn**
  - Cross section at 2200 m/s: 61100 and 259000 barn
  - Natural abundance: 14.8% and 15.7%
  - Many with $\gamma$ and $\alpha$ emission
Possible alternatives
Li – B – Cd - Gn
## Neutrons absorption cross section (thermal neutrons)

<table>
<thead>
<tr>
<th>Composition/Z</th>
<th>A</th>
<th>Neutrons absorption cross section at 2200 m/s [barn]</th>
<th>Density [g/cm³]</th>
<th>Mean free path [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6$Li</td>
<td>Z = 3</td>
<td>6.015</td>
<td>940</td>
<td>0.534</td>
</tr>
<tr>
<td>$^7$Li</td>
<td>Z = 3</td>
<td>7.016</td>
<td>0.0454</td>
<td>0.534</td>
</tr>
<tr>
<td>$^{10}$B</td>
<td>Z = 5</td>
<td>10.013</td>
<td>3835</td>
<td>2.08</td>
</tr>
<tr>
<td>$^{11}$B</td>
<td>Z = 5</td>
<td>11.004</td>
<td>0.0055</td>
<td>2.08</td>
</tr>
<tr>
<td>$^{155}$Gd</td>
<td>Z = 64</td>
<td>134.95</td>
<td>61000</td>
<td>7.88</td>
</tr>
<tr>
<td>$^{157}$Gd</td>
<td>Z = 64</td>
<td>136.94</td>
<td>259000</td>
<td>7.88</td>
</tr>
<tr>
<td>nat Gd $^{155}$Gd(14.8%) + $^{157}$Gd(15.7%)</td>
<td>157.25</td>
<td>42568</td>
<td>7.88</td>
<td>7.78*10^{-4}</td>
</tr>
<tr>
<td>nat Li $^6$Li(7.4%) + $^7$Li(92.6%)</td>
<td>6.94</td>
<td>70.5</td>
<td>0.534</td>
<td>3.06*10^{-1}</td>
</tr>
<tr>
<td>nat B $^{10}$B(20%) + $^{11}$B(80%)</td>
<td>10.81</td>
<td>767</td>
<td>2.08</td>
<td>1.13*10^{-2}</td>
</tr>
<tr>
<td>LiCO$_3$Si $^6$Li(95%) + $^7$Li(5%)</td>
<td>1.36</td>
<td>1.15*10^{-1}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Borated Polyeth</td>
<td>B(30%) + PolyEth(70%)</td>
<td>1.19</td>
<td>4.04*10^{-2}</td>
<td></td>
</tr>
</tbody>
</table>
Macroscopic cross section and mean free path

Macroscopic cross section (so called ???)

\[ \Sigma = \sum_i P_i N_i \sigma_i \]

- \( P_i \) = percentage in mass of \( i^{th} \) element
- \( N_i \) = number of nuclei per cm\(^3\) of the \( i^{th} \) element
- \( \sigma_i \) = microscopic cross section of \( i^{th} \) element

Mean free path

\[ \lambda = \frac{1}{\Sigma} \]

- \( \rho \) = density [g/cm\(^3\)]
- \( N_A \) = Avogadro number (6.022\( \times \)10\(^{23}\) atoms/mole)
- \( M \) = atomic weight [g/mole]
gadolinium

- is a silvery-white, malleable, and ductile rare earth metal
- is believed to be ferromagnetic at temperatures below 20 °C and it is strongly paramagnetic above this temperature.
- demonstrates a magnetocaloric effect whereby its temperature increases when it enters a magnetic field, and decreases when it leaves the magnetic field.
- Melting point: 1312 °C
- Density: 7.9 g/cm³
- Commercial material
- Non toxic
- Is widely used as a burnable absorber in nuclear power plants; gadolinium is very effective in compensation of the excess of reactivity

Check of availability, costs and delivered shape with specialized technicians and / or engineer. Check for enriched $^{157}$Gn
Configuration of 2015 run

LiCO$_3$  MM01  DC0  DC1  SM1
Run 2015 geometry
(special thanks to Genki)

- Li sheet (0.32cm)
- Polyethylene (1cm)
- Air gap
- Stainless steel 10cm
- Stainless steel 10cm
Pictures
(thanks to Genki)

2015 run guidelines

Maximum flexibility to control the particle flux downstream using different stainless steel thickness

- 0 cm
- 5 cm
- 10 cm
- 15 cm
- 20 cm
Material budget
(thanks to Genki)

Specifications of Li$_2$CO$_3$ & Si Rubber Sheet

- Dimension: 59 cm × 55 cm × 0.3175 cm
- Density: 1.36 g/cm$^3$

<table>
<thead>
<tr>
<th>A</th>
<th>Z</th>
<th>Mass ratio ((^6)Li vs (^7)Li)</th>
<th>Mass ratio (Li$_2$CO$_3$)</th>
<th>Mass ratio (Li$_2$CO$_3$ vs Si)</th>
<th>Mass ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^6)Li</td>
<td>6</td>
<td>3</td>
<td>95.00</td>
<td>18.79</td>
<td>30</td>
</tr>
<tr>
<td>(^7)Li</td>
<td>7</td>
<td>3</td>
<td>5.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>12.01</td>
<td>6</td>
<td>16.25</td>
<td></td>
<td>4.876</td>
</tr>
<tr>
<td>O</td>
<td>16.00</td>
<td>8</td>
<td>64.96</td>
<td>70</td>
<td>19.49</td>
</tr>
<tr>
<td>Si</td>
<td>28.09</td>
<td>14</td>
<td>70</td>
<td>70</td>
<td>70.00</td>
</tr>
</tbody>
</table>

Polyethylene

n * (C$_2$H$_4$)
Density: 0.94 g/cm$^3$
## Simulations

<table>
<thead>
<tr>
<th>name</th>
<th>Additional sheet</th>
<th>1st sheet</th>
<th>2nd sheet</th>
<th>3rd sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>MM01-ntg-10</td>
<td>Air (2015 configuration)</td>
<td>0.32 air</td>
<td>0.32 air</td>
<td>1 air</td>
</tr>
<tr>
<td>MM01-ntg-11</td>
<td>Lithium carbonated + polyethylene</td>
<td>0.32 Li</td>
<td>0.32 Li</td>
<td>1 polyeth</td>
</tr>
<tr>
<td>MM01-ntg-12</td>
<td>Borated polyethylene (B = 30%)</td>
<td>0.32 Bpol</td>
<td>0.32 Bpol</td>
<td>1 Bpol</td>
</tr>
<tr>
<td>MM01-ntg-13</td>
<td>gadolinium + polyethylene</td>
<td>0.32 Gd</td>
<td>0.32 polyeth</td>
<td>1 polyeth</td>
</tr>
</tbody>
</table>
MM01
flux of various particles
MM01
Energy of particles

Photons flux on MM01 detector

Neutron flux on MM01 detector
MM0-ntg-10 and 11 crossing point

10 air

11 Li
MM0-ntg-12 and 13 crossing point

12 Borated polyethylene

13 Gadolinium
## Summary of simulations

<table>
<thead>
<tr>
<th>simulation</th>
<th>Additional sheet</th>
<th>Thickness [cm]</th>
<th>phot/Pr</th>
<th>neutron/Pr</th>
<th>e-/Pr/cm^2</th>
<th>charg/Pr</th>
</tr>
</thead>
<tbody>
<tr>
<td>MM01-ntg-10</td>
<td>Air (run 2015)</td>
<td>0.32+0.32+1</td>
<td>2.145</td>
<td>1.762</td>
<td>0.109</td>
<td>0.219</td>
</tr>
<tr>
<td>MM01-ntg-11</td>
<td>Carbonated Lithium + polyethylene (run 2015)</td>
<td>0.32+0.32+1</td>
<td>2.259</td>
<td>1.600</td>
<td>0.119</td>
<td>0.230</td>
</tr>
<tr>
<td>MM01-ntg-12</td>
<td>Borated polyethylene (B = 30%)</td>
<td>0.32+0.32+1</td>
<td>2.383</td>
<td>1.328</td>
<td>0.108</td>
<td>0.230</td>
</tr>
<tr>
<td>MM01-ntg-13</td>
<td>Gadolinum+ polyethylene</td>
<td>0.32 + 1.32</td>
<td>2.411</td>
<td>1.616</td>
<td>0.127</td>
<td>0.234</td>
</tr>
</tbody>
</table>

Neutral = neutrons + photons + other  
Check with standard flka scoring

**Neutrons crossing MM1**  
- Lithium -9%  
- Borated polyethylene -25%

**Photons crossing MM1**  
- Lithium +5%  
- Borated polyethylene +11%
Suggestions from cheap to expensive

- Reshuffle the downstream stainless steel layers
  - Motivation: leave more material in the neutron source direction
    - Now: 5cm + 5cm + airgap + 10cm
    - Reshuffled: 10cm + 5cm + airgap + 5cm
  - Check the side bar suspensions and its buttonholes
- Remove the downstream Li layer and polyethylene
  - Simply wrong: always, put the moderator first and then a neutron absorber
- Replace the side suspensions with longer one
  - Leave more air gap between the last two layers
- Use natural borated polyethylene instead of Li
conclusions

- No impressive neutrons reduction even with the best neutrons absorbers (in theory)
- No relevant difference in XY distribution
- For neutrons flux reduction, borated polyethylene is better than carbonated lithium sheet
- For photons flux reduction, carbonated lithium is better than borathed polyethylene
- Check of vertex, momentum resolution etc, must be done using the standard Compass simulations tools.

But the basic question is:
The high rates is due to neutrons or photons interaction?
\( \gamma \) interaction with matter

![Graph showing linear attenuation coefficient versus photon energy with contributions from photoelectric absorption, Compton scattering, and pair production.

*Fig. 2.3* Linear attenuation coefficient of NaI showing contributions from photoelectric absorption, Compton scattering, and pair production.
\( \gamma \) interaction with matter

**Figure 32.15:** Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes [51]:

- \( \sigma_{\text{p.e.}} \): Atomic photoelectric effect (electron ejection, photon absorption)
- \( \sigma_{\text{Rayleigh}} \): Rayleigh (coherent) scattering—atom neither ionized nor excited
- \( \sigma_{\text{Compton}} \): Incoherent scattering (Compton scattering off an electron)
- \( \kappa_{\text{inc}} \): Pair production, nuclear field
- \( \kappa_{\text{e}} \): Pair production, electron field
- \( \sigma_{\text{G.D.R.}} \): Photonic nuclear interactions, most notably the Giant Dipole Resonance [52].

In these interactions, the target nucleus is broken up.

Original figures through the courtesy of John H. Hubbell (NIST).