Estia analysis of H1 and H2 events for radiation hazard

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This document uses a worst case scenario to evaluate the radiation hazard at a point outside the instrument shielding closest to the radiation source. The results are used to extrapolate the hazard on any point outside the instrument shielding. It is found that even for this event the Estia shielding already fullfills the requirements for normal operation (H1) and thus is sufficient for both scenarios.

Calculation of radiation hazard of an H2 event in Estia:

The event in question is a complete absorption of a fully open beam (maximum beam size passing through the stationary collimation without running chopper) at the sample position by Cd containing material and the subsequent emmission of γ-radiation that needs to be stopped at the experimental cave wall closest to the sample.

- Data for the attenuation coefficient in iron is taken from A. Poskus, Attenuation of Gamma Rays, Vinius University (2012) and extended to higher energies from NIST tables (http://physics.nist.gov/PhysRefData/XrayMassCoef/cover.html).
- Conversion factors for gamma area rate to dose rate uses ICPR-2 table.
- neutron to gamma conversion table from Evaluated Nuclear Structure Data File (ENSDF), which is experimentally validated.

In [1]:
```
from scipy.interpolate import interp1d, Rbf

# load energy dependent attenuation coefficient data for Pb and Fe and
# generate an interpolator to be able to calculate it for each energy
data_Fe=loadtxt('/home/glavic_a/Software/ipython/notebooks/gamma_attenuation/Fe_data.png.ext').T
data_Pb=loadtxt('/home/glavic_a/Software/ipython/notebooks/gamma_attenuation/Pb_data.png.ext').T
# smooth interpolation, as data is extracted from image and has therefore steps
mu_Fe=Rbf(data_Fe[0], data_Fe[1], smooth=25, epsilon=0.01)
mu_Pb=Rbf(data_Pb[0], data_Pb[1], smooth=25, epsilon=0.01)

# read table of energy dependent conversion coefficients
# from gamma rate per area to rem/hour: gamma/cm^2 s->rem/hr
ICPR2_conversion=loadtxt('/home/glavic_a/Software/ipython/notebooks/gamma_attenuation/conversion_factors.dat').T
gamma_rem=interp1d(ICPR2_conversion[0], ICPR2_conversion[1])

# read a list of γ-energy vs conversion probablility and select lines above 1% probability and 400 keV energy
txt=open('/home/glavic_a/Software/ipython/notebooks/gamma_attenuation/Cd_gammas.dat', 'r').readlines()
Cd_gammas=[]
for line in txt:
    line=line.strip()
    if line[0]=='#':
        continue
    try:
        cols=map(float, line.split())
    except ValueError:
```

```
            continue
        if len(cols)<3 or cols[2]<1.0 or cols[0]<=400.:
            continue
        Cd_gammas.append((cols[0]/1000., cols[2]/100.))
```

Constants used in the calculations.

```
In [2]: rem2muSv=1e4 # [(μSv/hr)/(rem/hr)]
        wall_distance=1690. # [mm] distance between sample position and closest point outside the cave wall
        n_rate=5e9 # [1/s] rate of neutrons that hit sample area
```

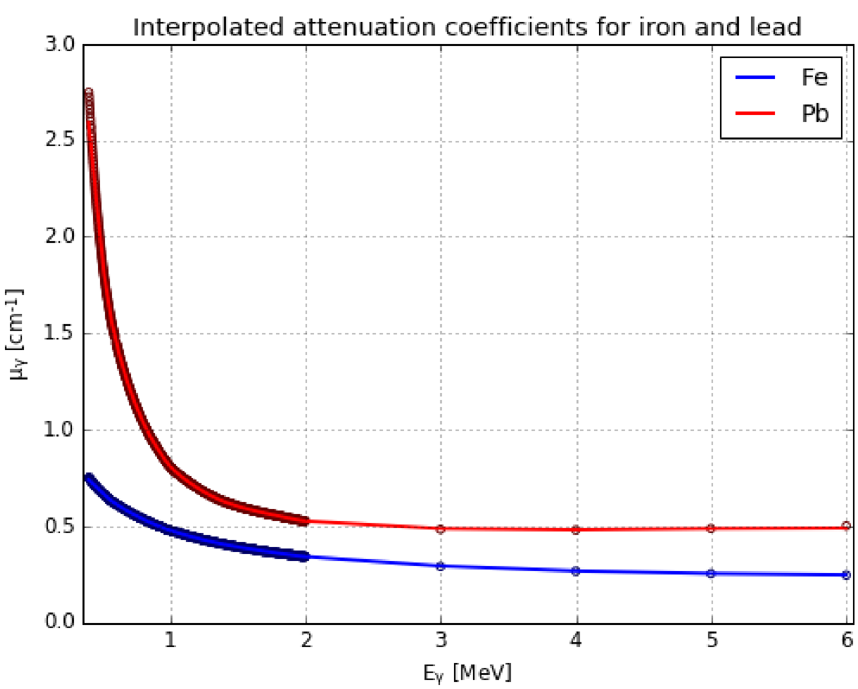
Attenuation factors for Fe and Pb dependant on energy and shielding thickness.

```
In [3]: def atten_Fe(E, d):
            return exp(-mu_Fe(E)*d)
        def atten_Pb(E, d):
            return exp(-mu_Pb(E)*d)
```

Show the accuracy of the smoothed attenuation coefficient for comparison with the mentioned publication.

```
In [4]: E=linspace(0.4, 6.0, 100)

        figure(figsize=(8.0,6.0))
        title('Interpolated attenuation coefficients for iron and lead')
        scatter(data_Fe[0], data_Fe[1], edgecolors='#000066', facecolors='none')
        plot(E, mu_Fe(E), 'b-', lw=2, label='Fe')
        scatter(data_Pb[0], data_Pb[1], edgecolors='#660000', facecolors='none')
        plot(E, mu_Pb(E), 'r-', lw=2, label='Pb')
        xlim(0.35, 6.05)
        xlabel(r'E$_\gamma$ [MeV]')
        ylabel(r'$\mu_{\gamma}$ [cm$^{-1}$]')
        grid()
        legend();
```



Perform the calculations for Cd absorption over a range of Fe and Pb shielding thicknesses

In [5]:
```
dFe=linspace(0., 160., 161)
dPb=linspace(0., 60., 121)
DFe, DPb=meshgrid(dFe, dPb)

A=4.*pi*(wall_distance/10.)**2
print u'Wall outer distance: %.3f m; sphere area: %.3g cm²'%(wall_distance/1000., A)

R=zeros_like(DFe)
for E, P in Cd_gammas:
    print u'γ(%.2f MeV) yield: %.1e'%(E, P*n_rate), ';   dose rate: %5.2f μSv/h'%(P*n_rate/A*gamma_rem(E)*rem2muSv)
    R+=P*n_rate*atten_Pb(E, DPb/10.)*atten_Fe(E, DFe/10.)*gamma_rem(E)*rem2muSv/A
print 'Total dose rate: %.3g μSv/h'%(R[0,0])
```

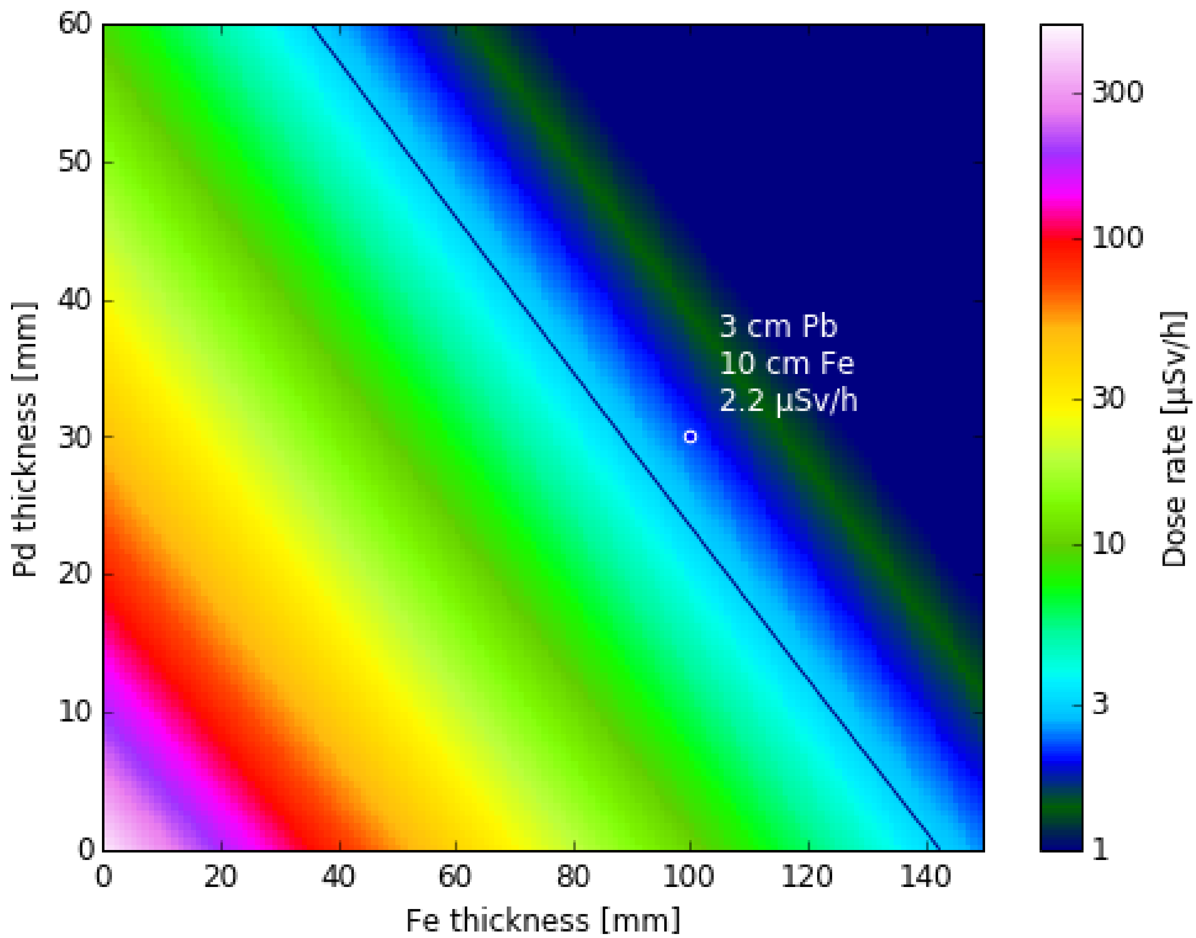
Wall outer distance: 1.690 m; sphere area: 3.59e+05 cm^2

γ **Energy [MeV]**	γ **yield [1/s]**	**dose rate [μSv/h]**	γ **Energy [MeV]**	γ **yield [1/s]**	**dose rate [μSv/h]**
0.56	$5.0 \cdot 10^9$	145.45	1.40	$2.3 \cdot 10^8$	14.93
0.58	$3.0 \cdot 10^8$	9.08	1.49	$1.6 \cdot 10^8$	10.82
0.65	$9.5 \cdot 10^8$	32.31	1.66	$1.9 \cdot 10^8$	13.74
0.65	$9.0 \cdot 10^7$	3.07	1.83	$7.4 \cdot 10^7$	5.82
0.71	$7.8 \cdot 10^7$	2.86	2.10	$6.2 \cdot 10^7$	5.45
0.73	$3.0 \cdot 10^8$	11.24	2.40	$5.2 \cdot 10^7$	4.90
0.75	$8.2 \cdot 10^7$	3.14	2.55	$1.0 \cdot 10^8$	10.23
0.81	$3.4 \cdot 10^8$	14.16	2.66	$1.9 \cdot 10^8$	19.02
1.21	$2.8 \cdot 10^8$	16.03	2.77	$7.6 \cdot 10^7$	8.05
1.28	$1.1 \cdot 10^8$	6.83	3.00	$8.0 \cdot 10^7$	8.86
1.30	$6.9 \cdot 10^7$	4.19	5.43	$7.8 \cdot 10^7$	12.73
1.31	$7.6 \cdot 10^7$	4.66	5.79	$5.4 \cdot 10^7$	9.27
1.36	$3.1 \cdot 10^8$	19.68	5.82	$2.0 \cdot 10^8$	33.90
1.37	$7.2 \cdot 10^7$	4.59	5.93	$5.4 \cdot 10^7$	9.34

Total dose rate: 444 μSv/h

Plot the resulting data

```
In [6]: figure(figsize=(8.0,6.0))
        pcolormesh(DFe,DPb,R, norm=LogNorm(1.0, 500.), cmap='gist_ncar')
        colorbar(label='Dose rate [$\mu$Sv/h]', ticks=[1.0, 3.0, 10., 30., 100., 300.]).\
              ax.set_yticklabels(['1', '3', '10', '30', '100', '300'])
        scatter([100],[30], edgecolors='w')
        text(105, 32, u'3 cm Pb\n10 cm Fe\n%.1f μSv/h'%(R[60,100]), color='w')
        contour(DFe, DPb, R, [3.0])
        xlabel('Fe thickness [mm]')
        ylabel('Pd thickness [mm]');
```



General conclusion for such H2 event:

As can be seen in the plot above, using 5 cm of Fe on the inside and 5 cm on the outside of the proposed wax can cave shielding in conjunction with 3 cm of Pb reduces the produced gamma radiation below a 3 μSv/h threashold. As most of the cave wall is much further away from the sample position then the evaluated wall it would be enough to add the lead layer on a selected area (2x2 m^2) closest to the sample. All other areas are at least twice as far away, reducing the radiation 4 times so that the pure iron shielding would be sufficient.

As the Estia guide system has only a small loss between the virtual source and the experimental cave and the heavy collimation inside the bunker wall eliminates most fast neutrons, the given scenario is sufficiently similar to evaluate these areas, as well. In the guide section all neutrons will be absorbed by either Boron or Lithium. The Boron absorption produces a softer gamma emission and the steel thickness in that area is 20 cm, therefore the dose rate will be far below the same threashold. Lithium absorption in the shutter has no gamma emission, but produces fast neutrons with an efficiency below 10^{-5}. Although the conversion coefficient from fast neutrons to dose rate is much larger than for gamma radiation, the yield is low enough that the minimal distance to the radiation source alone is sufficient to reach the 3 μSv/h threashold and no further shielding considerations are necessary.

Expansion to normal operation hazard (H1):

As shown above, the Estia shielding reduces the radiation hazard of the complete absorption of all neutrons that could ever reach the experimental cave below a 3 μSv/h level. Any other set of operational parameters (different sample, smaller virtual source) will reduce this by orders of magnitude. This is the given threashold value for normal opetions of ESS instruments and is therefore safely fullfilled with the Estia shielding concept.

Beamstop Considerations:

While the instrument beamstop will be closer to the outer wall of the cave (2-3 times), the absorber to be used is Boron and the wall behind it will contain at least 30 cm of iron shielding material. Although no separate calculation has been carried out, the increase of iron thickness alone will be sufficient to reach a safe level supported by the lower gamma emission energy.