Radioactivity Abundance in Simulation

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July 25, 2011

Abstract

This note gathers information about radioactivity rates in the AD and converts the rates to abundances used in simulation.

1 Measurements

Table 1 lists radioactivity measurements in different components of Antineutrino Detector (AD) [1, 2, 3].

	gds(TDR)	lso(TDR)	PMT(Doc 2576)	sst(Doc 2495)	rock(Doc 2576)
U^{238}	10^{-3} ppb	10^{-3} ppb	131(2) ppb	<0.0012 Bq/kg	10.8(1) ppm
Th^{232}	10^{-3} ppb	10^{-3} ppb	256(5) ppb	0.006(2) Bq/kg	31.6(3) ppm
K^{40}	10^{-3} ppb	10^{-3} ppb	0.0115(3)%(K)	0.013(4) Bq/kg	3.52(2)%
Co^{60}				<0.002 Bq/kg	

Table 1: Radioactivity measurements

[4] has more detailed measurements about PMT and stainless steel (AD ladders and rails). The results of PMT components are shown in Table 2.

	U^{238}(ppb)	Th^{232}(ppb)	K^{40}(ppm)	Co^{60}(mBq/kg)	mass(kg)
Bond epoxy	122±2	146±4	211±4	0.0	0.017
Oil-proof epoxy	<1	<3	<2	0.0	0.472
Semi-flexible lead	30±10	<10	<10	0.0	0.009
Magnetic shield foil	<0.4	<0.7	<0.5	0.0	0.020
Stainless steel mount	<0.9	$5^{+8.7}_{-5.0}$	<2	26±8.2	0.213
Low-background glass	153±25	335±90	165.6±45	0.0	0.809
Dynode metal structure	17±3	24±10	<3	32±5	0.065

Table 2: Radioactivity measurements for the parts of PMT assemblies [4]

From [5], we have 23.373×0.855=20.0 tons gd-doped liquid scintillator, 25.102×0.855=21.5 tons undoped liquid scintillator, 19 tons stainless steel.

2 Conversion factor

There are some ambiguities in converting ppb to Bq/kg. Table 3 lists the conversion factors used in different documents. Let's first get familiar with the units "ppb"and "Bq". "ppb" means 1 part per billion, 1 ppm=1000 ppb, 1 Bq=1 s^{-1}. Most of the conversion factors in Table 3 agree each other, though with small differences. However, there is big difference for K^{40}, Doc 2576 doesn't agree with Doc 1408 and Doc 3545, while the later two agree with each other. There might be a difference in definition. The conversion factor used in Doc 2576 may have also considered the K^{40}natural abundance (0.0117%). If we include K^{40}natural abundance in the calculation, the result will agree.

In oder to clarify things and also get the convertion factor for Co^{60}, we show the process of getting the convertion factors here. Suppose we have 1 kg of material with 1 ppb concentration of Co^{60}. How many Co^{60}do we have? It is 1 ppb$\times$ 1 kg$\times$ N_A/m(1 mol Co^{60}) $= 10^{-9}\times 10^3\times N_A/59.9338222$, where $N_A = 6.022 \times 10^{23}\,\mathrm{mol}^{-1}$ is the Avogadro constant. The half life of $Co^{60}$is $T_{1/2}(Co^{60})$=5.2714 year, so

$$\frac{dN}{dt}(Co^{60}) = -\lambda N = -\frac{\ln 2}{T_{1/2}}N = -4.19 \times 10^7\, s^{-1}. \tag{1}$$

1 ppb Co^{60}= 4.19×10^7 Bq/kg. Similarly, we can do the calculations for U^{238}, Th^{232}, and K^{40}. The results are shown in Table 4. All the numbers agree with Table 3, the small difference can be safely ignored.

	Doc 1408	Doc 3545	Doc 2576
U^{238}	1 ppb = 12.4 mBq/kg	1 ppb = 12.4 mBq/kg	81 ppb = 1 Bq/kg
Th^{232}	1 ppb = 4.0 mBq/kg	1 ppb = 4.1 mBq/kg	246 ppb = 1 Bq/kg
K^{40}	1 ppb = 258.4 mBq/kg	1 ppb = 265.1 mBq/kg	32.3 ppm = 1 Bq/kg

Table 3: Conversion factors used in different documents

	Half Life	Atomic mass	Conversion
U^{238}	4.468×10^9 years	238.0507826	1 ppb = 12.4 mBq/kg
Th^{232}	1.405×10^{10} years	232.0381	1 ppb = 4.1 mBq/kg
K^{40}	1.277×10^9 years	39.9639987	1 ppb = 259.4 mBq/kg
Co^{60}	5.2714 years	59.9338222	1 ppb = 4.19×10^{10} mBq/kg

Table 4: Calculated convertion factors

3 Abundances

What is used in GenDecay package is number of isotopes. By using N=concentration$\times$mass$\times N_A$/m(per mole), one can get Table 5. Notice that Table 2 is used for radioactivity calculation in the 192 PMTs, while the rest are calculated based on Table 1.

For rock, we assume the volume is 11×17×11 - 10×16×10 = 457 m^3. The density is set to 2.5 ton/m^3.

	gds	lso	PMT	sst	rock
U^{238}	5.06e+16	5.43e+16	6.21e+19	4.65e+18	3.12e+25
Th^{232}	5.19e+16	5.57e+16	1.38e+20	7.22e+19	9.37e+25
K^{40}	3.01e+17	3.23e+17	4.71e+19	1.43e+19	6.06e+29
Co^{60}			3.51e+8	9.11e+9	

Table 5: Number of isotopes in different components

4 IBD rates

Here, we also enclose a section for Inverse Beta Decay rates, which are used in mock data generation. There are 1047.9 IBD events per day for 1.462×10^{30} free protons[8] at Daya Bay near site. By using the number of free protons in [5], one can get the rates, which are shown in Table 6.

	gds	iav	lso	oav	oil
Free protons(Doc4217)	1.54e+30	4.16e+28	1.65e+30	9.21e+28	3.32e+30
Rates (s^{-1})	0.013	3.5e-4	0.014	7.6e-4	0.028
Lifetime (s)	78.4	2896.1	73.0	1309.2	36.3

Table 6: IBD reactions rates in different components of AD

References

[1] TDR

[2] Doc-2576

[3] Doc-2495

[4] Doc-4529

[5] Doc-4217

[6] Doc-1408

[7] Doc-3545

[8] Doc-2546