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Efficiency of Neutron Capture on D in pure D_2O from sources in the AV and the H_2O

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The analytic expressions for neutron efficiency developed in SNO-STR-2000-029, entitled "The Efficiency and Lifetime of Neutrons in the SNO Detector" can be used to estimate the number of neutrons produced by radioactivity in or on the AV and which capture on deuterium in the pure D_2O running phase. Equation (25) gives the efficiency for a spherical shell source (or a point source) of neutrons at distance s from the centre of the detector. Since γ-rays of Th and U which photo-disintegrate the deuteron have a linear attenuation coefficient μ of about 4.34 m^{-1}, neutrons will tend to be produced near the AV from a source on the AV or in the H_2O, and hence s will always remain close to R, the radius of the AV. Hence equation 25 can rewritten as

$$\in = \frac{\lambda_D}{\lambda}\left\{1 - \frac{R}{s}e^{(s-R_e)/\ell}\cdot A\right\} \qquad \textbf{(1)}$$

where R_e is the extrapolated distance of neutron density (ref. 1), λ_D and λ are the neutron decay constants in D and in D_2O, ℓ is the diffusion length and

$$A = \cosh\left(\frac{R_e - R}{\ell}\right) + \sinh\left(\frac{R_e - R}{\ell}\right). \qquad \textbf{(2)}$$

This ∈ must be averaged over all places s within the D_2O where the primary γ-ray emitted from radius R is absorbed, and include the photon-neutron conversion factor. The final result is that

$$\langle\in\rangle = \frac{1}{2}\cdot\frac{\lambda_D}{\lambda}\cdot\frac{1}{n_\lambda}\left\{1 - \frac{1}{2\mu R} - Ae^{(R-R_e)/\ell}\cdot\mu\ell\cdot\ln\left(1+\frac{1}{\mu\ell}\right)\right\} \qquad \textbf{(3)}$$

where n_γ is the number of γ rays required to produce one neutron by photodisintegration of the deuteron. Equation (3) has been written to expose separately the various physical effects; these are in sequence the factor ½ which is the fraction of inward directed γ-rays, λ_D/λ as the fraction of neutrons capturing on deuterium in D_2O, $1/n_\lambda$ as the photon-neutron conversion factor and {} which is the fraction of neutrons not diffusing and absorbing in the surrounding acrylic and/or H_2O. On the assumption that the source is on the inside surface of the acrylic vessel, the efficiency for a 2.615 MeV γ-ray to produce a neutron which captures on the deuteron is

$$\langle \in \rangle = \frac{1}{2}(0.53)\frac{1}{470}0.148 = 8.35\times 10^{-5} \qquad \textbf{(4)}$$

using ℓ = 1.23 m, μ = 4.34 m^{-1}, R_e = 6.16 m and n_γ = 470. As an example, if the acrylic contains 10^{-12} g/g of Th on the inside surface, and has a mass of 30 tonnes, then the number of neutron-generated 6.25 MeV γ-rays per day is ~0.32 using the fact that 126 γ-rays/d are emitted by 1 μg of ^{232}Th in equilibrium. If the source is on the outside surface of the acrylic a separate calculation shows that due to source γ-ray absorption the efficiency drops to $\langle\epsilon\rangle \simeq 5.0 \times 10^{-5}$ and the number of 6.25 γ-rays per day is 0.19. The average number of 6.25 MeV γ-rays is about 0.25/day per 10^{-12} g/g in the AV, or about 0.1/day if the AV contamination is about 4×10^{-13} g/g as expected from radioactivity measurements on the acrylic. For the uranium series, 16.8 γ-rays of 2.445 MeV are emitted per day by 1 μg of ^{238}U in equilibrium, and n_γ is 750. Hence 10^{-12} g/g of U in the acrylic would produce only 0.02 neutrons per day capturing on the deuteron. These numbers are considerably smaller than the canonical ones of the White Book, where only the numbers of neutrons produced are estimated and not the number capturing on deuterium. The dominant extra reduction is the factor 0.148 in (4) which is the numerical value of {} in (3). The

effects of thermalization of the photo-produced neutrons has been neglected in the present calculations.

Radon in the H_2O emits 2.445 MeV γ-rays and can also produce neutrons in the D_2O. The flux of 2.445 MeV γ-rays from a uniform source S(m^{-3} d^{-1}) in the H_2O incident on the outer acrylic surface is (White Book, p. 75)

$$\Phi = \frac{S \cdot 4\pi R^2}{4\mu} \qquad \textbf{(5)}$$

The flux on the inside of the acrylic is then reduced by about $e^{-\mu x}$, where x is the acrylic thickness, and then one can use the efficiency for a source on the inside surface of the acrylic, equation (3), but leaving out the factor of ½ (which is already included in eq. (5)). Hence the efficiency is

$$\langle \in \rangle = \frac{\lambda_D}{\lambda} \cdot \frac{1}{n_\lambda} (0.148)\, S \frac{\pi R^2}{\mu} e^{-\mu x} \,. \qquad \textbf{(6)}$$

where 0.148 is the term in brackets of eq. 3. Hence

$$\langle \in \rangle = \frac{\lambda_D}{\lambda} \cdot \frac{1}{n_\lambda} \left(3.10\, m^3\right) S \qquad \textbf{(7)}$$

(an exact calculation replaces the factor 3.10 by 3.14) and the average efficiency for producing a neutron capture on deuterium from the 2.445 MeV γ-ray from the H_2O is 2.2×10^{-3} $m^3 \cdot S$ At 10^{-12} g/g of equilibrated ^{238}U in the H_2O, S is 16.8 γ-rays/m^3-d, and therefore H_2O at this level of purity will produce 3.7×10^{-2} neutrons capturing on the deuteron per day. This value is 3-4% of the canonical value quoted in the White Book (p. 76). The difference is primarily due to the high probability of loss of neutrons to the acrylic and the fact that only about one-half of the neutrons remaining capture on the deuteron.

During the two large radon spikes that went into the H_2O on Nov. 17 and Nov. 20, Henry Lee (private communication) estimates that a maximum of 8×10^8 radon atoms entered the region between the AV and the PSUP. Using the fact that 1.5% of radon decays produces a 2.445 MeV γ-ray, eq. 7 suggests that there were at most 15 captures on D from these spikes, assuming that the radon was fairly uniformly distributed through the 1700 m^3 of inner H_2O.