Neutron Production in SNO due to Calibration Techniques

J.R. Leslie

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1 Introduction

The introduction of radio-nuclides into the detector can produce an increase in the background wall or more seriously if the radioactive decay is energetic enough can produce free neutrons in the D_2O volume. The most harmful contaminants which are likely to be introduced in the calibration procedures are ^{24}Na and ^{222}Rn as these yield decay γ rays of 2.75 and 2.45 MeV respectively. The ^{24}Na can be produced in the D_2O by activation of the ^{23}Na in the added NaCl either by neutrons from calibration devices or, in the case of the D_2O external to the detector shielding, by background neutrons. Radon can be introduced to the detector by air exchange when calibration glove boxes are placed on the top of the vessel neck and by diffusion through and emanation from containment materials. Thoron (^{220}Rn), although in principle a harmful contaminant, has been ignored in the discussion as its short half life makes its emanation from materials highly improbable.

1

2   Neutron activation of D_2O

It is assumed that neutrons introduced into the D_2O will thermalise in the D_2O and the relative rates of capture can be deduced from the relative atom density and the appropriate thermal capture cross section σ_γ. The possibility of escape from the D_2O has been ignored. For 99.85% D_2O containing 0.25% by weight of NaCl the relative capture probabilities are given in the table below.

Nuclide	σ_γ (b)	% capt	$t_{\frac{1}{2}}$	Radiation
H	0.333	3.3	stable	
D	0.00052	3.3	12.3 a.	β^- (18keV)
^{16}O	0.00019	0.6	stable	
^{17}O	0.0004	-	stable	
^{18}O	0.00016	-	26.9 s.	β^- (4.6,3.5 MeV) γ (<1.5 MeV)
^{23}Na	0.53	1.5	15 h.	β^- (1.39 MeV) γ (1.37,2.75 MeV)
^{35}Cl	43.6	91.2	3×10^5a.	β^- (0.7 MeV)
^{37}Cl	0.43	0.3	37.3 m.	β^- (4.9,2.7 MeV) γ (1.6,2.1 MeV)

2.1   Activation by Neutron based Calibration Sources

If a neutron source is placed at the centre of the detector neutrons which leak from the source will be captured in the D_2O and solute. As a long term effect ^{24}Na is the only nuclide which looks problematic. For a worst case we consider the ^3He source - with a 2.2×10^5 neutron per second ^{252}Cf source and a neutron leakage of 1.2% immersed in the D_2O for 24 h. The count rates immediately after source removal are as follows:

Nuclide	$t_{\frac{1}{2}}$	decays/h.	neutrons/h.
T	12.3 a.	42.	0
^{19}O	26.9 s.	108	0
^{24}Na	15 h.	9.6×10^4	203
^{36}Cl	3.0×10^5 a.	1.48	0
^{38}Cl	37.3 m.	2.8×10^4	0

The rate of neutron production by ^{24}Na is reduced by a factor of 3.0 per day so that the rate will become less than 2 per day after 8 days in the case of the large source, in place for 24 hours, with a neutron leakage of 2.6×10^3 per second into the D_2O. A smaller neutron source of say 100 s^{-1} will give rise to a proportionally lower rate, but will still take 5 days to decay to the normal background level. Small sources in for short times will of course give reduced activation - the subsequent neutron production rate due to ^{24}Na decay is then proportional to source insertion time and is given by $0.08\times t$ neutrons per day for a source of 1 neutron per second where t is the insertion time in hours. So a 100 neutron per second source inserted into the D_2O will give an initial ^{24}Na induced neutron production rate of 8 per day for each hour the source is in the detector reducing by a factor of 10 for each 2 day wait.

2.2   Activation of D_2O when Stored

In this case details of the circulation system and the time spent in holding tanks is of importance so the calculation has been done for a possible but not necessarily realistic case. It is assumed that the D_2O is held in a 1.5 m. radius by 2.8 m. high right cylindrical tank and that the contents of the tank are pumped into the vessel in a time short compared to the lifetime of ^{24}Na. If the neutron flux through the tank walls is 3000 m^{-2}day^{-1} and all neutrons incident on the cylinder are absorbed the neutron production rate in the D_2O due to background induced ^{24}Na is 4 per day and this production give rise to a similar decay rate in the vessel if the pumps are running. The neutron flux is that measured[1] to come through the drift

3

walls. This may not be a mode in which we run the detector - but there will be large external tanks and we have to consider the consequences of various operating modes.

If we use an accelerator to activate materials (such as a ^{16}N production system) then the neutrons produced can cause a background due to neutron leakage followed by ^{24}Na production. The neutrons production rate for this method is similar to the source strength for the ^{3}He source and the shield will likely leak at least 1% of neutrons produced. The actual activation rate in the heavy water depends on geometry and the mode of water system operation - but even with full water flow and high estimates of neutron entry to the D_2O the interference should be much less than that produced by a 100 neutron per second source immersed in the D_2O of the detector vessel.

3 Radon Entry to the D_2O Volume

3.1 Air Exchange

When the "glove boxes" are put in place to insert calibration devices they must be flushed to remove ^{222}Rn. If the box was to contain Rn at the mine air level of 2.0 pCi/ℓ and had a volume of 1 m^3 then there would be 3.5 $\times 10^7$ ^{222}Rn atoms, which if fully mixed into the D_2O gives 1490 neutrons produced in the detector with an initial daily rate of 390 and a die down time of 29 days to a 2 neutron per day rate. A reduction in glove box radon by a factor of 1000 would reduce this background to a tolerable level. This means that we should aim for a maximum of 1.0×10^{-3} pCi/ℓ in the glove box gas when the box is opened to the cover gas on top of the D_2O. The glove boxes will have a sliding seal which will normally be in place to prevent dust and Rn ingress. When the box is put in place on top of the neck the small volume between its seal and the sealing valve on top of the neck will be flushed with N_2, produced by boil off from liquid nitrogen, prior to the removal of seals. Sources and other systems will be introduced to the interior of the glove box by gas flushable air-lock style pass throughs. Glove ports will be provided to enable work to be carried out in the box.

3.2 Diffusion and Emanation of Radon

The materials that the sources and source containers are constructed from can act as sources of Rn in that the interior surfaces will emanate Rn and that Rn will diffuse through the walls of the containers. A treatment of this problem is given in more detail by Bigu $etal$[2] For an infinite slab in the steady state the diffusion equation describing the concentration (C) of Rn in materials is as follows:

$$D\frac{\partial^2 C}{\partial x^2} - \lambda C + R = 0 \tag{1}$$

Here x is the coordinate perpendicular to the plane of the slab, D is the diffusion coefficient for the material, λ is the decay constant for Rn and R is the production rate of Rn per unit volume. For the ^{238}U decay chain in equilibrium R is given by $\lambda_{238} N_{238}$ where λ_{238} and N_{238} are the decay constant and number per unit volume of ^{238}U atoms, respectively.

The flow of Rn from wall material into the cover gas is then described by the current density J:

$$J = -D\frac{\partial C}{\partial x} \tag{2}$$

The above equations without the creation term will describe the permeation current (J_P) of Rn through the walls of glove boxes and for wall thickness (τ) large compared to $\sqrt{D/\lambda}$ the solution is given by:

$$J_P = 2C_1 S \sqrt{\lambda D}\, e^{-\sqrt{\frac{\lambda}{D}}\tau} \tag{3}$$

where C_1 is the Rn concentration in the air outside the box and S is the solubility (that is the ratio of atom density just inside to just outside a surface) of Rn in the wall material.

For emanation from a surface of a thick slab the current density (J_E) is given by:

$$J_E = R\sqrt{\frac{D}{\lambda}} \qquad (4)$$

The total flow of Rn into the cover gas will be given by:

$$J = J_P + J_E \qquad (5)$$

In the equilibrium situation the Rn decay rate will be equal to the rate of introduction. The sum must be done over all materials in the glove box and emanation rates for some materials will have to be taken from experiment as the effective surface area of many materials is not known.

3.2.1 Estimates of Emanation Rates

For a material with a specific gravity of one with a ^{238}U concentration of 2.5 $\times 10^{12}$ atoms/cm^3 (1ppb by weight) we have $R = 1.23 \times 10^{-5}$ cm^{-3} s^{-1}. For ^{222}Rn $\lambda = 2.1 \times 10^{-6}$ s^{-1} and using the acrylic value [3] of $D = 6.2 \times 10^{-10}$ cm^2 s^{-1} we get a Radon emanation rate of 182 atoms m^{-2} day^{-1} which, if fully mixed in the D$_2$O, would give 2.5 neutrons per year for each square metre.

3.2.2 Estimate of Permeation Rates

The exponential factor in equation (3) is 9×10^{-17} for 0.25″ acrylic. With mine air of 2 pCi/ℓ, $C_1 = 35$ atoms/cm^3 and $S = 8.2$ for acrylic [2] we have $J_P = 8.6 \times 10^{-13}$ atoms m^{-2} day^{-1}. This rate is very low and it seems clear that permeation through normal box materials will present no background problems. Pass throughs and actual glove materials will likely give rise to elevated permeation rates. In the case of Butyl rubber gloves of thickness 2 mm. with the diffusion and solubility constants from Wojcik[3] the permeation rate is 404 atoms m^{-2} day^{-2}. This again is a small rate and will only give rise to 6.5 background neutrons per year.

3.3 Overall Entry of Rn into the Cover Gas Volume

It seems to be possible to design and install (including exchange of boxes) calibration equipment without unduly increasing the detector background. Some special attention will have to be paid to seals, glove systems and pass-throughs.

4 References

1. G.T. Ewan et al. SNO Report SNO-85-3. (The Blue Book) 79.

2. J. Bigu, E.D. Hallman and L.Kendrick. SNO Report SNO-STR-91-069.

3. M. Wojcik, Nucl. Instrum. Meth. Phys. Res. B61 (1991) 8.