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Fast Neutrons from Muon Spallation in the SNO Detector

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1 Introduction:

Neutrons from muon spallation reactions have a very hard spectrum, with energies well into the hundreds of GeV. They constitute a potentially significant background in the SNO detector because they may penetrate the water blanket around the detector and be captured in the fiducial volume. This report contains an estimate of the rate of neutrons entering the detector due to this process, and concludes that it is small relative to the signal rate: the number of neutrons entering the D_2O is not more than 0.1/day and may be lower than 2 per year, depending on how the estimate is made, and how efficient the muon veto is.

2 Muon Flux:

The muon flux at SNO depth can be estimated from data taken by the FREJUS collaboration [1]. These data consist of measurements of the muon flux at various slant depths, corrected for the angular distribution of muons at the surface. The data are well fit by:

$$I_o(h) = K_o[\frac{h_o}{h}]^2 \exp(-h/h_o) \tag{1}$$

with $K_o = 1.96 \times 10^{-2} m^{-2} s^{-1} sr^{-1}$ and $h_o = 1184 hg/cm^2$. The flux through a horizontal surface at a depth d can be estimated by integrating this flux between zenith angles of 0 and $\pi/3$. For zenith angles greater than $\pi/3$

the flux is dominated by muons produced by neutrino interactions in the surrounding rock. The flux is:

$$\mathcal{F}(d) = 2\pi \int_0^{\pi/3} \frac{\sin\theta I_o(d/\cos\theta)}{\cos\theta} d\theta + 2\pi \int_0^{\pi} \sin(\theta) 2 \times 10^{-9} d\theta \qquad (2)$$

where d is the detector depth in m.w.e. The flux is in muons/(m^2 s). The second term in equation 2 only contributes a few percent to the total flux.

3 Detector Depth:

The norite rock around the detector has properties that vary strongly as you move away from the ore body [2]. Norite density varies between 2.78 g/cm^3 and 3.0 g/cm^3. The average value of Z/A for norite is 0.5, the same as standard rock, and $\overline{(Z/A)^2}$ is 5.26, slightly lower than the standard rock value of 5.5. For our purposes, norite can be treated as standard rock. The footwall rock has a density of 2.71 g/cm^3, and is quite far away ($\sim$ 1000 m) from the detector. The footwall rock is quite inhomogeneous, and as we far out on the tail of the muon distribution, these inhomogeneities could conceivably dominate the muon flux at the detector. The mine workings themselves are also a significant perturbation to the flux which has not been taken into account here.

Assuming the rock above the detector has a density of 2.9 g/cm^3, the detector is at a depth of 5940 m.w.e. A depth of 6000 m.w.e. will be used in what follows. Using equation 2, a depth of 6000 m.w.e gives a muon flux of $4 \times 10^{-6} \mu/m^2 s$.

4 Spectral Shape and Average Energy:

The spectral shape is not strictly relevant to the calculation at hand, but I've calculated it so here it is [3]. The spectral shape at some depth is determined by taking the spectrum at the surface and transporting it to some depth using a transport equation. A simple transport equation for muons is:

$$\frac{dE}{dX} = -\alpha - \frac{E}{\xi} \qquad (3)$$

where α is the continuous energy loss ($\sim$ 2 MeV/(g/cm^2)) and ξ characterizes discrete interactions such as bremsstrahlung, pair production and hadronic interactions. For rock, ξ is about 2500 m.w.e.

Region	r (m)	A (m^2)	V (m^3)	muons/day
D_2O	6	113	905	39
PSUP	8.5	114	1667	39
ROCK	11	153	3003	53
total				131

Table 1: Throughgoing Muons in the SNO Detector

The average energy of muons that start at the surface of the Earth with energy E_s and travel a slant depth X is given by:

$$\overline{E} = (E_s + \varepsilon)\exp(\frac{X}{\xi}) - \varepsilon \qquad (4)$$

where ε is the energy at which continuous and discrete energy losses are equal. For rock, this is about 500 GeV.

The spectral shape at the surface can be approximated as depending on $E_s^{-2.7}$. The spectral shape at a depth d is therefore given by:

$$\frac{dN_\mu}{d\overline{E}}(d) \propto \int_0^{\pi/3} [(\overline{E} + \varepsilon)\exp(\frac{d}{\xi\cos(\theta)})]^{-2.7} \exp(\frac{d}{\xi\cos(\theta)})\tan(\theta)d\theta. \qquad (5)$$

This integral can be evaluated numerically, and gives results not too far from those of Cassiday, Keuffel and Thompson [4], who use a more exact form for the spectrum at the surface and a more realistic transport equation. The only interesting thing that comes out of this analysis is that the average muon energy at SNO depth is between 500 and 600 GeV.

5 Throughgoing Muons:

The SNO detector can be modeled as concentric spheres. Table 1 shows the outer radii and other properties of the three detector regions. Note that the areas, volumes and muon rates of the outer layers are for those layers alone, and not the regions within them.

6 Stopped Muons:

Determining the number of stopped muons is difficult. Cassiday et al [4] estimate that there should be about 4×10^{-3} stopped for every muon that goes through 1 m.w.e. at depths of greater than 2000 m.w.e. Taking the effective thickness of the SNO detector to be just the ratio of the volume to the area (i.e. 8.8 m.w.e) this gives 1.4 stopped muons per day in the fiducial volume. Kamiokande, however, reports seeing about 400 stopped muons per day for 34,600 throughgoing at a depth of 2700 m.w.e with an effective thickness of 15.6 m.w.e. Scaling this number to the SNO detector gives only 0.26 stopped muons per day. To make matters worse, there have been measurements suggesting that Cassiday et al's model is low by a factor of about 4. A more complete survey of the literature may throw some light on this problem.

Using the spectral shape calulated above, a crude esitmate of the fraction of stopped muons can be made by looking at the number of muons with energies of less than 1.75 GeV (assuming 2 MeV/cm energy loss in water, and a path length of 8.8 metres.) Integrating the spectral shape given by equation 5, this gives a stopped muon fraction in the D_2O of 0.6%, or 0.24 stopped muons per day. This is in agreement with the number predicted by the Kamiokande data. For all muons within the PSUP, the maximum energy for stopping is 2.4 GeV, assuming an average path length of 12 m.w.e. This gives 0.8% stopped muons, or 0.64 per day.

7 Fast Neutrons from Rock:

There are a variety of ways of estimating the fast neutron flux from spallation reactions. The cross-section for virtual photoexcitation of a nucleus is about 4 μb per nucleon and the nucleon density in rock is $\sim 10^{25}/\mathrm{cm}^3$. The neutron multiplicity for a typical spallation induced shower is 4. This gives a rate of about 5×10^{-14} neutrons/(g s) at a depth of 6000 m.w.e.

The fast neutron production rate has been measured at a depth of 5200 m.w.e. [5] which is sufficiently close to SNO's depth to be useful. The measured value is 2×10^{-13} neutrons/(g s). Scaling for depth, this is in reasonable agreement with the simple estimate given above. A nominal value of 5×10^{-14} neutrons/(g s) will be assumed.

If we consider neutrons from the rock only, and treat the detector as a slab geometry, the rate of neutrons entering the D_2O is given by:

$$6\pi \int_{1100}^{\infty} 5 \times 10^{-14} r^2 \exp(-4.7) \exp(-3(r-1100)/150) dr \qquad (6)$$

where a neutron absorption length of 150 g/cm^2 has been assumed. The 12 π in front of the integral is a 4 π from the volume integration and a factor of 3 from the rock density and a factor of 1/2 from solid angle (i.e. half the neutrons go away from the detector.) This integral gives a rate of neutrons entering into the D_2O of $\sim 10^{-6}$ neutrons/second = 0.1 neutrons/day.

There has also been a direct measurement of the flux of neutrons with energies greater than 0.7 GeV [6]. Using a 100 T scintillation detector a flux of 15 neutrons/year/100 m^2 was measured at 5300 m.w.e. Integrating over the surface of the SNO cavity this corresponds to 228 neutrons per year leaving the rock. These will be attenuated by a factor of $e^{-4.7}$ passing through the light water, giving 2 neutrons per year at the acrylic vessel.

If we treat the detector geometry as concentric spheres, there is an additional factor of about 4 due to the lower solid angle of the acrylic vessel as seen from the rock. A realistic detector geometry of a sphere inside a cylinder will produce even lower numbers due to the greater attenuation of the neutron flux through the thicker water blanket away from the waist.

8 Fast Neutrons from H_2O:

Taking the nucleon density in light water to be $\sim 10^{25}$ /cm^3 and the production cross-section and multiplicity as above, the production rate of fast neutrons from muon spallation in the water between the rock and the PSUP is around 5×10^{-14} /(g s), as it is in the rock. This assumes a muon flux of 4×10^{-10} μ/(cm^2 s). A concentric spherical geometry gives 3000 tonnes of water in this region. 10,000 tonnes will be assumed. This gives a production rate of $10^{10}g \times 5 \times 10^{-14}(gs)^{-1} \times 86400s/day = 43$ neutrons/day created by muons in this region.

Many of these neutrons will be accompanied by muon signals inside the PSUP. This is given by the ratio of solid angles of the PSUP and the cavity, which is roughly the ratio of the their cross-sectional areas ($8.5^2/11^2 = 0.6$), so 40% of the muon induced spallation neutrons in the outer light water region will not be accompanied by muon signals in the detector. The total rate in the D_2O will be (assuming a spherical geometry which gives an average solid-angle factor of 0.4 for inward-going neutrons):

$$2\pi 0.4 \int_{850}^{1100} 5 \times 10^{-14} r^2 \exp(-1.7) \exp(-(r-850)/150) dr \qquad (7)$$

which evaluates to 0.2 neutrons/day. This is with no vetoing outside the PSUP. A 50% efficient veto outside the PSUP would reduce this number to 0.1 neutrons/day. Again, treating the detector as a sphere inside a cylinder would be a better approximation, and would reduce this rate further.

As a final consideration, the total mass inside the PSUP is about 2700 tonnes, so the production rate of neutrons by spallation is 12 per day, or a spallation rate of 3 per day. There are about 80 muons per day passing through the detector inside the PSUP, of which 40 intersect the D_2O. This means that about 4% of throughgoing muons will produce spallation events inside the PSUP.

9 Conclusion:

The rate of neutrons entering the fiducial volume from muon spallation events in the rock is very small: between 2 and 40 neutrons per year, assuming a slab geometry. A concentric spherical geometry gives numbers in the range of 0.5 to 10 neutrons per year from the rock, and treating the cavity as a cylinder will reduce these numbers further.

The neutron rate from spallation events in the water outside the PSUP is slightly higher, as much as 70 per year without any veto outside the PSUP, and assuming a concentric spherical geometry. This number is an upper limit on the number of neutrons from this process. The utility of a muon veto external to the PSUP is primarily as a means of measuring these neutrons, rather than as a means of getting rid of them.

References

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