Spent Nuclear Fuel Contributions to P15A Data Set

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Abstract

Antineutrinos from stored β-decays of spent nuclear fuel (SNF) are expected to contribute to the IBD signal observed in the Daya Bay detectors. The contribution from SNF to the observed flux in the near hall detectors for the P15A data set is calculated to be 0.39% averaged over the full P15A data set. The fractional energy spectrum as well as the effect of displacement of the spent fuel pools from the reactor cores is calculated.

Although previous groups have calculated the SNF fraction for partial data sets [5][10][8][7][11][6][12], no calculation has included the entire P15A data set. For comparison with previous analyses, the fractional contribution from SNF to the IBD flux in the near halls for 31 weeks of data beginning at Dec. 24, 2012 (P12A dataset) in this investigation is calculated to be 0.27% in agreement with previously quoted 0.3(0.3)% contributions [1]. For the larger dataset quoted in [2], the fractional SNF contribution is found to be 0.36% in decent agreement with the quoted 0.3(0.3)%.

1 Introduction

Most nuclear reactors used for power generation use enriched uranium oxide as their fuel. Reactors are typically refueled every 1-2 years with the oldest 1/3 of the fuel rods replaced with new ones. The old fuel rods, which are still very radioactive, are then mechanically transferred from the reactor through a water channel to a spent fuel pool to "cool down." A few radioactive isotopes in the spent fuel rods have sufficiently long half-lives and high enough energy to produce a neutrinos that will be detected by the Daya Bay AD's. Previous groups have calculated the fractional flux spectrum of SNF events from nuclear reactors similar to the Daya Bay reactors[5][8]. For this investigation, I chose to use a newer calculation by Xubo Ma *et al.*[12] not only because it is the newest calculation, but also because it more representative of conditions at Daya Bay.[1] This spectrum (see Fig. 3 of [12]) is shown in

[1] The calculation by Zhou Bin *et al.*[5] assumes a"typical" 1 GW PWR reactor running for 331 days after which all the fuel is considered SNF. No further specifics are given and as such it is difficult to apply properly to the Daya Bay and Ling Ao reactors. The newer calculation specifies a 45 GWd/tU burnup and assumes 1/3 of the core becomes SNF which is considered to be representative of the reactors under consideration.

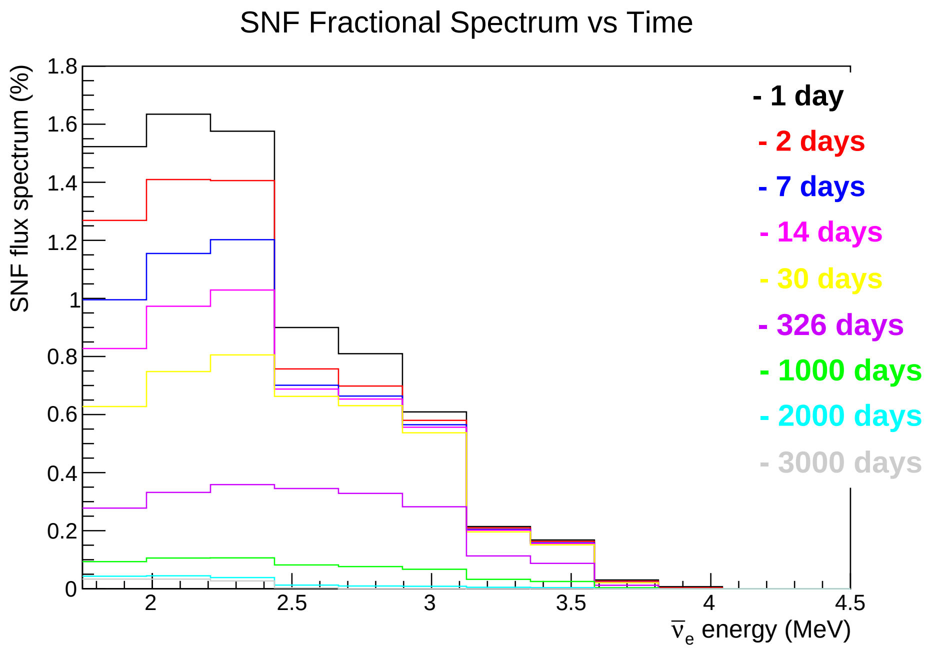

Figure 1: Fractional SNF spectrum calculated by Xubo Ma *et al.* [12].

Figure 1.

2 Methodology

Every time a reactor is refueled additional SNF is added to the storage pools located in a hall close by the reactor containment building. That spent fuel quickly decays so that within a few weeks its contribution to the reactor antineutrino flux is well below 1%. Calculating the SNF flux spectrum at a given detector location for the Daya Bay experiment requires summing the contributions from all spent fuel as a function of its age since removal from the reactor and its location. Each contribution must be weighted by $1/L^2$, the distance between the pool and the location of interest. The fractional SNF flux spectrum at the location of a given detector d can be given as follows[2]:

$$S_{frac}^{\mathrm{SNF}} \approx \frac{S_d^{\mathrm{SNF}}}{S_d} = \frac{\sum_{r=1}^{6}\left(\sum_{i=1}^{N_r} P_{r,d}^{\mathrm{sur}}(E,\tilde{L}_{r,d}) S_r^{\mathrm{SNF}}(E,t-t_{r,i})\right)/\tilde{L}_{d,r}^2}{\sum_{r=1}^{6}\frac{P_r(t)P_{r,d}^{\mathrm{sur}}(E,L_{r,d})}{L_{d,r}^2}S_r(E)}, \tag{1}$$

where S_d^{SNF} is the total SNF flux spectrum from the six reactor SNF pools and S_d is the total reactor flux spectrum at detector d. The sum over r is the sum over the six reactors and i goes

[2] An exact expression should include an extra term in the denominator i.e. $S_{frac}^{\mathrm{SNF}} = \frac{S_d^{\mathrm{SNF}}}{S_d+S_d^{\mathrm{SNF}}}$, but since $\frac{S_d^{\mathrm{SNF}}}{S_d}$ is $\sim$1% this second order term is omitted.

over all N_r refuel times where new SNF was added to the pools. $L_{d,r}$ is the distance between reactor r and detector d, and $\tilde{L}_{d,r}$ is the distance between detector d and the SNF pool for reactor r. The results are weighted by the survival probability for neutrinos originating in the reactor core $P^{\text{sur}}_{r,d}(E, L_{r,d})$ and those originating in the SNF pools $P^{\text{sur}}_{p,d}(E, \tilde{L}_{r,d})$. $S^{\text{SNF}}_r(E,t)$ is the $\bar{\nu}_e$ flux spectrum from reactor r at time t since refuel. $t_{r,i}$ gives the times when reactor r is refueled measured since the beginning of P15A. Since all six reactors have equal thermal power output (2.9 GW$_{th}$), $S_r(E) \equiv S(E)$ is a constant w.r.t. the summation and Eq. 1 can be re-arranged as follows:

$$\frac{S^{\text{SNF}}_d}{S_d} = \frac{\sum_{r=1}^{6}\left(\sum_{i=1}^{N_r} P^{\text{sur}}_{r,d}(E, \tilde{L}_{r,d}) S^{\text{SNF}}_r(E, t - t_{r,i})/S(E)\right)/\tilde{L}^2_{d,r}}{\sum_{r=1}^{6}\frac{P_r(t)P^{\text{sur}}_{r,d}(E,L_{r,d})}{L^2_{d,r}}}, \tag{2}$$

With a couple of modifications, we can replace $S^{\text{SNF}}_r(E, t - t_{r,i})/S(E)$ with the simulated fractional spectra from Fig. 1 which we will refer to as $\rho(E,t)$. The spectra in Fig. 1 were calculated assuming that 1. the reactor burnup of the SNF was 45 GWd/tU and 2. 1/3 of the core was replaced during each refuel and becomes SNF. In order to accommodate these assumptions we add two factors α_r and δ_r such that

$$\frac{S^{\text{SNF}}_r(E,t)}{S(E)} = \delta_r \alpha_r \rho^{\text{SNF}}(E,t),$$

where, as previously mentioned, $\rho^{\text{SNF}}(E,t)$ is the calculated fractional SNF spectrum from [12] and shown in Fig. 1. The factor α_r is a burnup factor to account for SNF removed from the reactor core that is either more or less burnt up than the assumed burnup of 45 GWd/tU in the simulation. In reality α_r is a complicated function of reactor enrichment and the length of time and position in the core; however, for the purposes of this calculation it is simply assumed to be 1 for the Ling Ao cores and 4/3 for the Daya Bay cores (see Sec. 3.1 for details). δ_r is a reactor off scale factor which takes the value 1.0 when reactor r is on and 2.0 when it is off. This scale factor accounts for the fact that when a reactor is off, the entire core becomes effective SNF. Putting this all together gives

$$\frac{S^{\text{SNF}}_d}{S_d} = \frac{\sum_{r=1}^{6}\left[\alpha_r \delta_r \sum_{i=1}^{N_r} P^{\text{sur}}_{p,d}(E, \tilde{L}_{d,r}) \rho^{\text{SNF}}_r(E, t - t_{r,i})\right]/\tilde{L}^2_{d,r}}{\sum_{r=1}^{6} P_r(t) P^{\text{sur}}_{r,d}(E, L_{d,r})/L^2_{d,r}}. \tag{3}$$

3 Components of the SNF Spectrum Calculation

Before using Eq. 3 to calculate the spectrum we must determine the different terms used in the calculation.

3.1 Burnup α_r

As previously mentioned, the burnup of the SNF removed from a reactor depends on the reactor design, the fuel enrichment, the placement of the fuel in the reactor and the length of time the rods have been "burning" in the core. A simulation of a typical single refuel cycle for Daya Bay reactor 1 is given in Figure 4 of [3] showing that the expected burnup is 20 GWd/tU per refuel cycle. This means that the SNF removed after 3 cycles will have ∼60 GWd/tU burnup or about 4/3 the assumed 45 GWd/tU in the calculated spectra[12]. Given that both Daya Bay reactors are nearly identical in design and operation, I assumed a burnup scale factor of 4/3 for both. A more precise calculation of the burnup for SNF removed prior to August 2011 was performed for the study in [12] (see Figure 4 in [12]). Here the authors show calculated burnup for Daya Bay reactors 1 and 2 and Ling Ao reactors 3 and 4 for 5-10 years prior to 2011. During the five years before P15A it appears that the Daya Bay reactors had a burnup factor close to 1.3 reaffirming the 60 GWd/tU burnup obtained from the model in [3]. During the same 5 year period prior to August 2011, Ling Ao reactors 1 and 2 had a much smaller calculated burnup factor. The authors state that they have assumed a burnup factor of 1 for Ling Ao reactors 1 and 2 in the absence of further information. Since I have no information on the burnup other than looking at the fuel cycles, I have assumed a burnup during and before P15A of 4/3 for the Daya Bay reactors and 1.0 for all Ling Ao reactors.

To further justifying this assumption I looked at the refuel cycles of the various reactors. Fig. 3 shows the fractional reactor output versus time for the six reactors in P15A as well as the evolution of the ^{235}U fuel fraction. From this one can see that the fuel cycle for the Daya Bay reactors is about 18 months, whereas for Ling Ao 3 and 4 the cycle is closer to 12 months. Ling Ao reactors 1 and 2 have an intermediate refuel period perhaps around 15 months. Notice that for all the reactors refueling happens when the ^{235}U fraction is 40-50% suggesting that the Ling Ao reactors are running on less enriched fuel. Less enriched fuel also means less burnup per cycle as can be seen in Figure 2 taken from [9]. This leads to the conclusion that the Ling Ao reactors are using less enriched fuel and thus have smaller burnup factors. Thus in the absence of a model of burnup as a function of fuel fraction for each reactor, I simply chose to use the 45 GWd/tU assumed in the model.

3.2 Reactor off scale factor δ_r

As previously mentioned, during the period that the reactor is off for refueling, all the fuel in the core is "effective" SNF. One third of the fuel is 1 cycle old, one third is 2 cycles old, and one third is 3 cycles old for an effective two cycle age. Since the SNF neutrino flux is approximately proportional to burnup, the 2/3's of the fuel that remains in the core emits about the same flux of neutrinos as the 1/3 removed. Thus the reactor off scale factor is defined as follows:

$$\delta_r = \begin{cases} 1.0 & P_r(t) > 0 \\ 2.0 & P_r(t) = 0 \end{cases}. \tag{4}$$

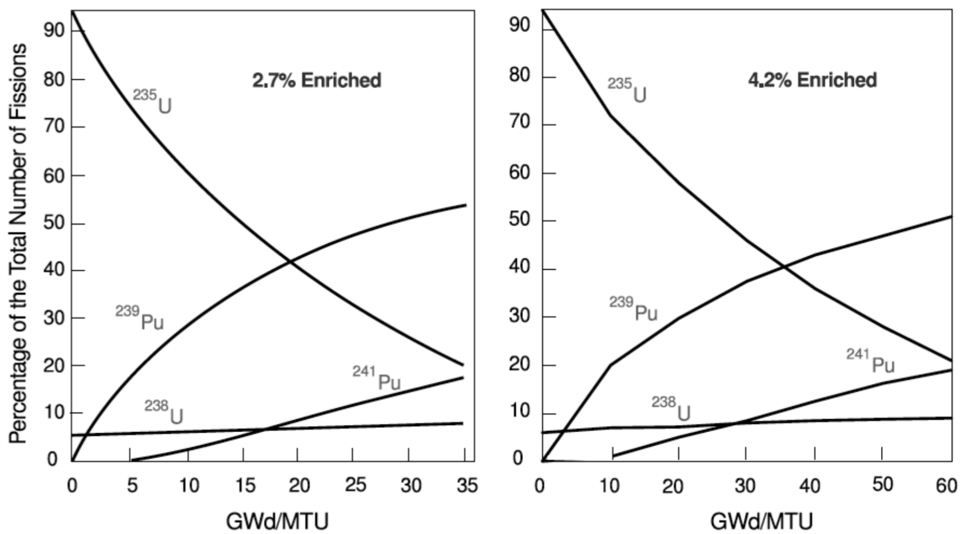

Figure 2: Fuel fraction evolution as a function of burnup for reactors utilizing fuel with different levels of enrichment. Figure taken from [9].

3.3 Survival probability $P_r^{\rm sur}(E, L)$

The neutrino survival probability $P^{\rm sur}(E_\nu, L_i)$ is given by the simple two-neutrino oscillation formula

$$P^{\rm sur}(E,L) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(1.267\Delta m^2_{21}\frac{L}{E}\right) - \sin^2 2\theta_{13}\sin^2\left(1.267\Delta m^2_{ee}\frac{L}{E}\right) \quad (5)$$

where $\sin^2 2\theta_{12} = 0.846$, $\sin^2 2\theta_{13} = 0.0841$, $\Delta m^2_{21} = 7.53\times10^{-5}$ eV^2, $\Delta m^2_{ee} = 2.5\times10^{-3}$ eV^2, and E is the energy of the neutrino. Including the survival probability only slightly changes the results at the location of the near detectors.

3.4 Reactor power $P_r(t)$ and refuel times $t_{r,i}$

All of the 6 reactors at the Daya Bay complex are rated at thermal power output of 2.9 GW$_{th}$. Neutrino flux is proportional to thermal output. The power company has provided fractional power output averaged over each week for each reactor. Plots of fractional reactor thermal output versus week in P15A can be seen in Fig. 3.

To determine the dates each reactor was refueled during P15A, one simply looks for reactor off times associated with a significant increase in the ^{235}U fuel fraction. The refuel weeks for each reactor which can be picked off the plots in Fig. 3, are given in Table 1.

To account for the history of SNF placed in the pools prior to P15A, I assumed a history of 5 refuels at 18 month intervals[3] for the Daya Bay reactors for a total of 7-8 years before

[3]The assumption of regular intervals for refueling rather than actual refuel times is due to lack of information. Per private communication with Xubo Ma, this information is not available. However, since the SNF

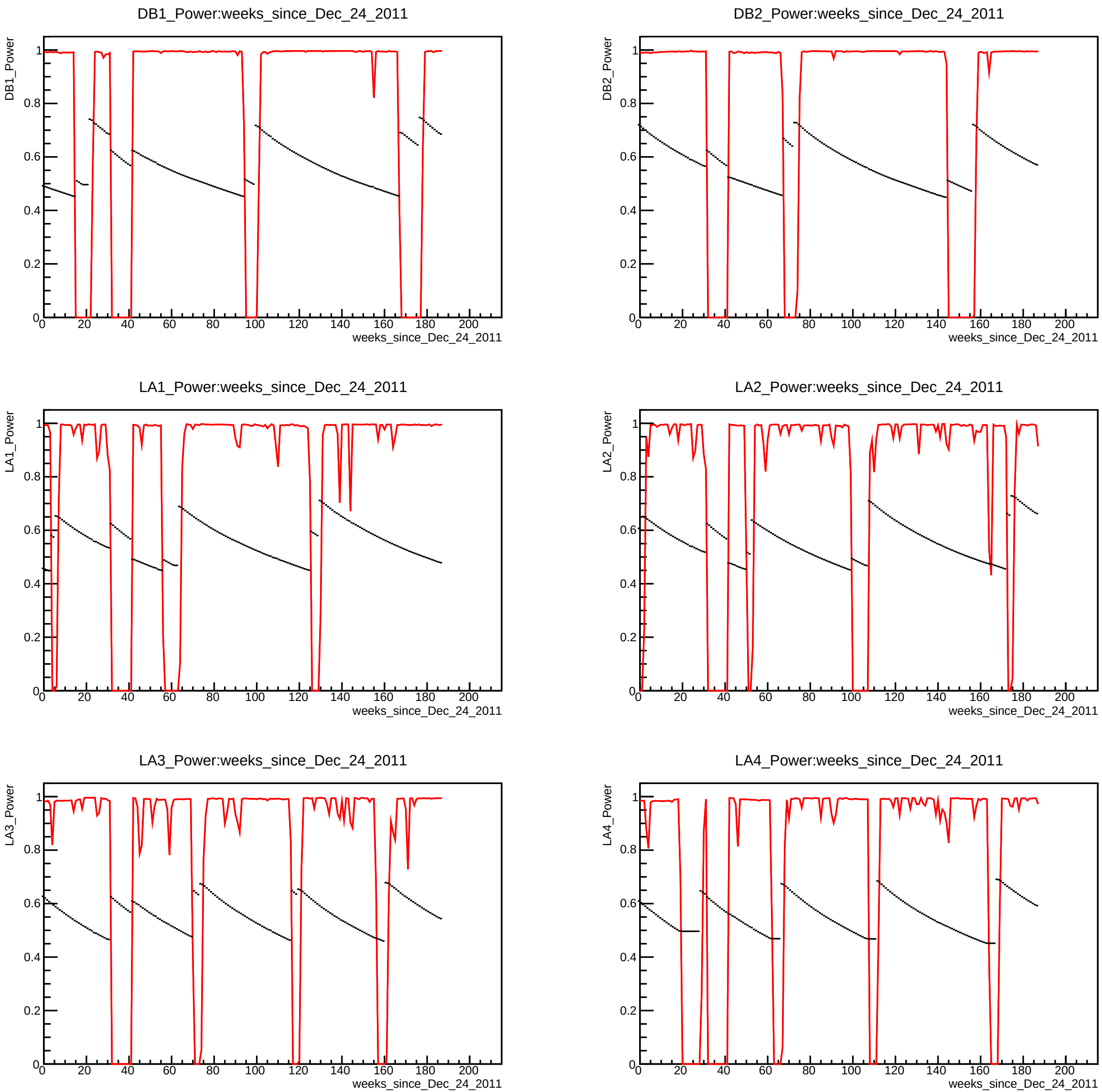

Figure 3: (Red) Fractional reactor power output versus week since beginning of P15A. (Black) Also shown are ^{235}U fuel fraction evolution. After each refuel the ^{235}U fraction jumps up.

Table 1: Refuel times for each reactor during P15A measured in weeks from Dec. 24, 2011.

Reactor	Refuel Times (week in P15A)
Daya Bay 1	15, 95, 168
Daya Bay 2	68, 145
Ling Ao 1	4, 57, 126
Ling Ao 2	51, 100, 173
Ling Ao 3	32, 71, 117, 157
Ling Ao 4	20, 63, 108, 165

the start of P15A, while for Ling Ao reactors 1 and 2, I assumed a history of 7 refuels prior to P15A at 12 month intervals. Ling Ao reactors 3 and 4 had come online shortly before the start of P15A. I assume a single refuel prior to P15A for Ling Ao 3 and no refuels prior to P15A for Ling Ao 4. For all reactors, the refuels at regular intervals before P15A count backwards from the first recorded refuel during P15A. Including this history has a significant impact on the calculation. For example, the calculated fraction of the signal in EH1-AD1 from SNF IBD events during P15A increases from 0.30% when no refuel history prior to to P15A is included to 0.44% when a 7 year history is included. However, increasing the history from 7 years to 10 years backward only increases the fractional antineutrino flux from SNF by 0.01% to 0.45%.

3.5 Baseline distances $L_{r,i}$

The survey group on the Daya Bay experiment provided precise locations of the detectors, reactors and the SNF pools in a 3D coordinate system where x is aligned along the North/South direction, y along East/West and z points upward[6]. These coordinates are given in Tables 2, 3 and 4. The distances between reactors, SNF pools and detectors are calculated using the distance formula:

$$L_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}$$

3.6 Parameterization of $\rho(E,t)$

This analysis utilizes a parameterization of the calculated points in Fig. 1. The parameterization is a quadruple exponential decay with 8 fit parameters (4 amplitude and 4 decay constant parameters). This parameterization provides a smooth, continuous, decreasing function of time that easily allows evaluation for any time. The step-wise structure of the

quickly decays, the older SNF contributes only about 30% of the total SNF signal in P15A. Using estimated times for refuel instead of actual times does not significantly impact the results (see Sec 5.1).

Table 2: Surveyed position coordinates of detectors.

Detector	x (m)	y (m)	z (m)
EH1-AD1	362.833	50.421	-70.817
EH1-AD2	358.804	54.858	-70.814
EH2-AD1	7.652	-873.488	-67.524
EH2-AD2	936.749	-1419.013	-66.485

Table 3: Surveyed position coordinates of reactors.

Detector	x (m)	y (m)	z (m)
Daya Bay 1	359.203	411.490	-40.231
Daya Bay 2	448.002	411.002	-40.239
Ling Ao 1	-319.666	-540.748	-39.730
Ling Ao 2	-267.063	-469.205	-39.723
Ling Ao 3	-543.284	-954.702	-39.799
Ling Ao 4	-490.691	-883.152	-39.788

Table 4: Surveyed position coordinates of SNF pools.

Detector	x (m)	y (m)	z (m)
Daya Bay 1	355.2	382.7	-36.2
Daya Bay 2	456.5	382.2	-36.2
Ling Ao 1	-298.714	-560.870	-35.674
Ling Ao 2	-238.707	-479.257	-35.666
Ling Ao 3	-522.330	-974.821	-35.743
Ling Ao 4	-462.333	-893.200	-35.731

energy spectrum is retained. Figure 4 shows plots of the parameterization functions plotted over the calculated points from the spectrum of Ma *et al.* [12].

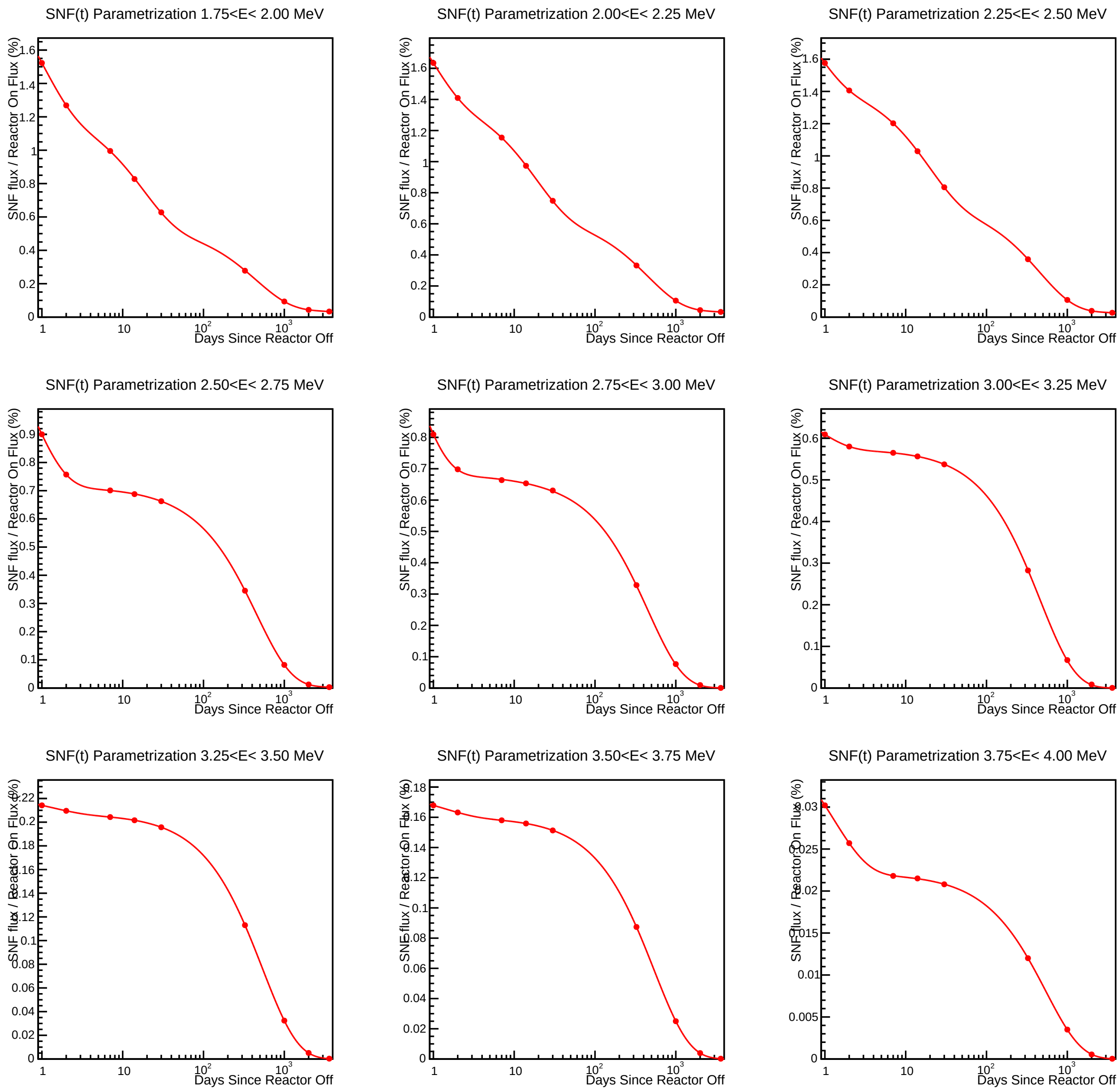

Figure 4: Parameterization of SNF decay curves for 9 energy bins from Fig 1 demonstrating the good agreement with the calculated data points.

4 SNF spectrum results

Using Eq. 3 along with the results of Section 3, we can proceed to calculate the fractional antineutrino spectrum. The SNF spectrum for each of the four near detectors averaged over P15A is shown in Figure 5. The mean of all the near detectors is shown in Fig. 6. The fractional spectrum is highest in the 1.8-2.5 MeV range and quickly drops off to a negligible fraction above 4 MeV. The detectors in EH1 have a significantly larger component from SNF than the EH2 detectors. This effect arises because most of the signal in EH1 comes from the two Daya Bay reactors whereas the signal in EH2 detectors comes primarily from four reactors. When one Daya Bay reactor shuts down the signal drops fractionally much more than it does in EH2 detectors when a single Ling Ao reactors shuts down.

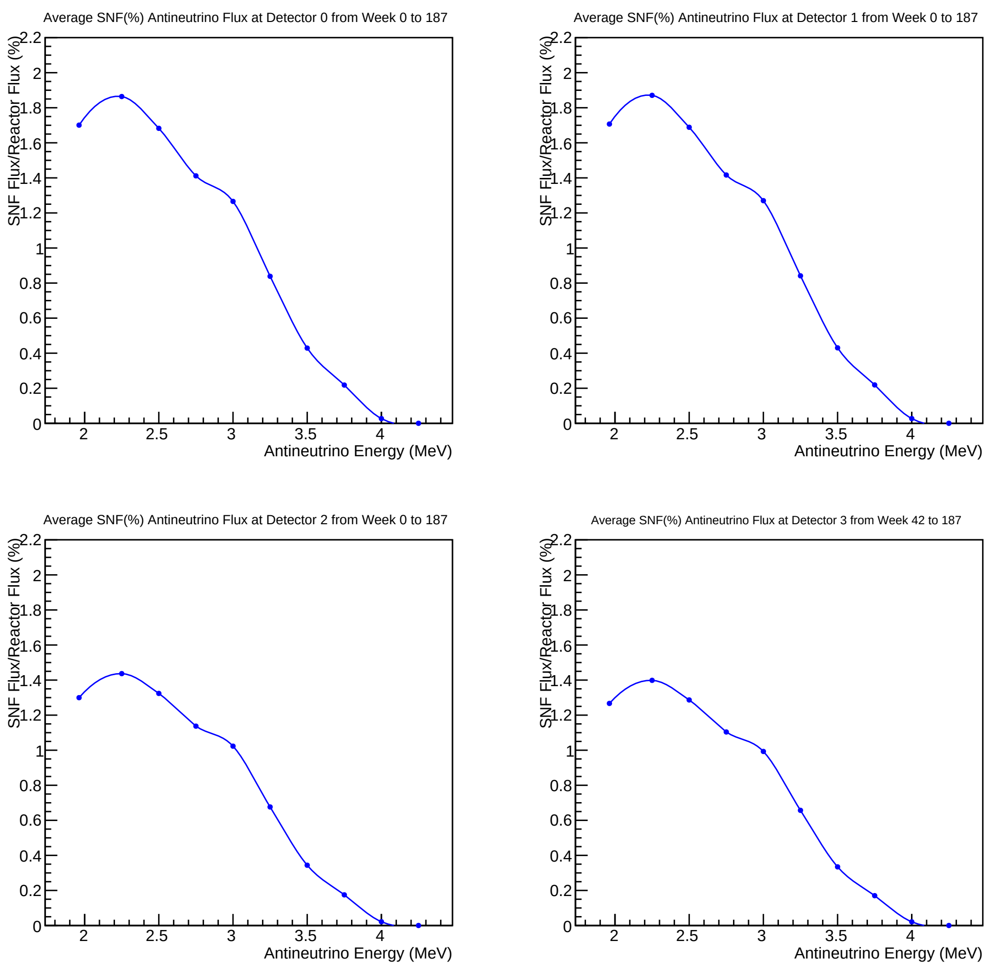

Figure 5: SNF spectrum for each of the four near detectors averaged over P15A. The curve connecting the data points is a cubic spline and not part of the calculation. Notice that Detector 3 (EH2-AD2) did not come online until week 42.

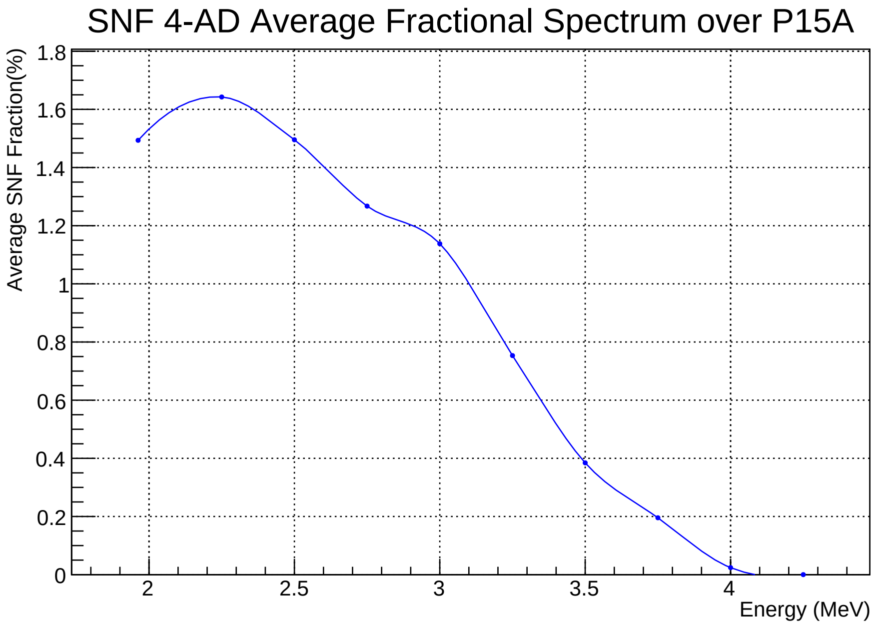

Figure 6: Near hall 4-detector mean SNF spectrum averaged over P15A. The curve connecting the data points is a cubic spline and not part of the calculation.

The expected detector IBD spectrum is needed in order to calculate the total fractional flux from SNF over a given energy range. For the fractional SNF flux calculations in this study I use the near hall IBD average spectrum given in Fig. 3 of [4]. The fractional SNF flux for a given energy range is then given by the following equation:

$$\frac{N_{\mathrm{IBD}}^{\mathrm{SNF}}}{N_{\mathrm{IBD}}^{\mathrm{nh}}} = \frac{\int_{E_{\mathrm{low}}}^{E_{\mathrm{high}}} S_{\mathrm{frac}}^{\mathrm{SNF}}(E) S_{\mathrm{IBD}}^{\mathrm{nh}}(E) dE}{\int_{E_{\mathrm{low}}}^{E_{\mathrm{high}}} S_{\mathrm{IBD}}^{\mathrm{nh}}(E) dE}, \tag{6}$$

where $N_{\mathrm{IBD}}^{\mathrm{SNF}}$ is the number of IBD events from SNF and $N_{\mathrm{IBD}}^{\mathrm{nh}}$ is the total number of IBD events in the near halls. $S_{\mathrm{IBD}}^{\mathrm{nh}}$ is the near hall average IBD spectrum and $S_{\mathrm{frac}}^{\mathrm{SNF}}$ is given by Eq. 3. Using Eq. 6 and integrating over the full IBD spectrum from 1.8-12 MeV gives the fraction of expected IBD events from SNF in the near hall detectors. Fig. 7 shows the SNF fraction versus time over P15A for each of the four near hall detectors and Fig.8 gives the straight average of the four detectors yielding an overall $\sim 0.4\%$ contribution. Notice that the proximity of the reactor to the detector can be gauged by the height of the spike in the SNF versus time plots.

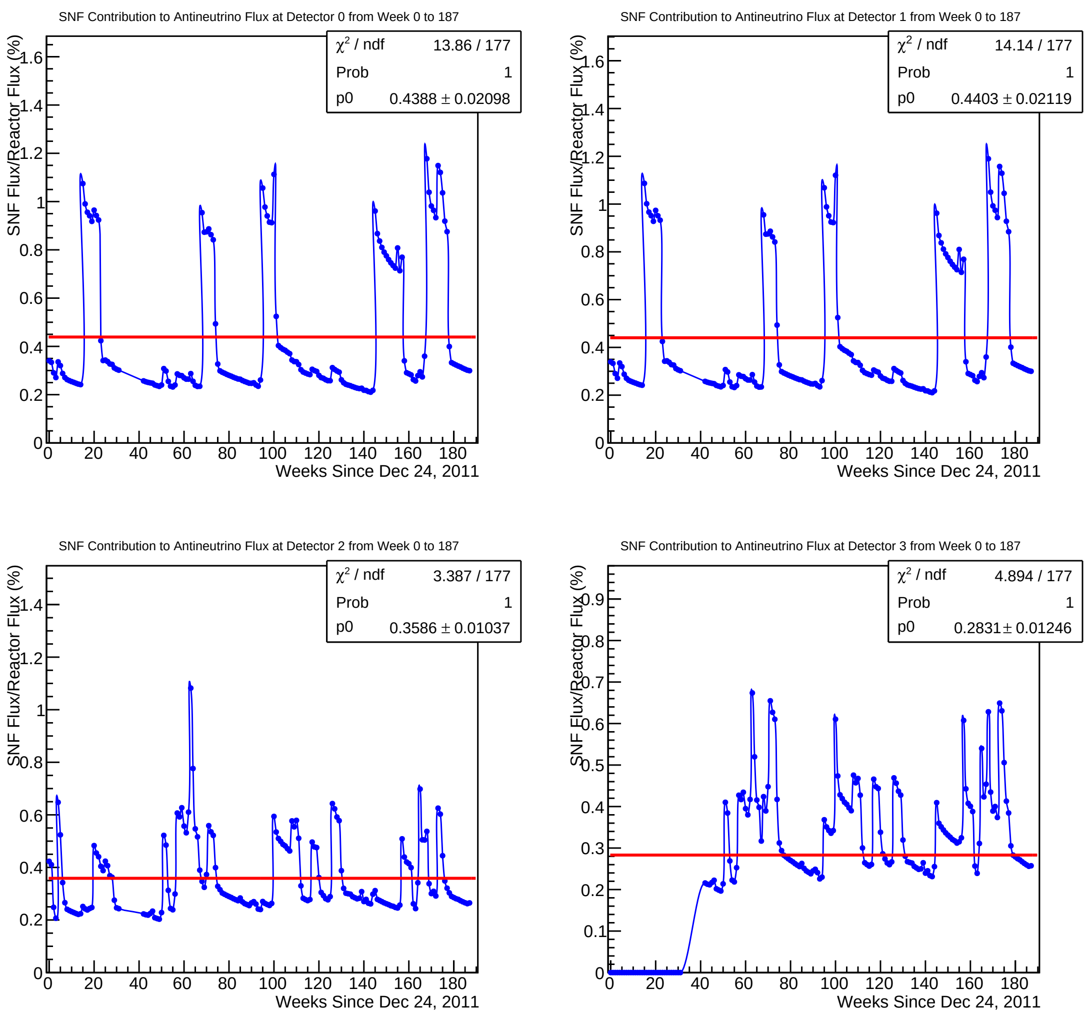

Figure 7: SNF fractional contribution over P15A for each of the near hall detectors. Notice that Detector 3 (EH2-AD2) did not come online until week 42. Each sudden increase in SNF comes from a reactor shutdown, most often for refueling.

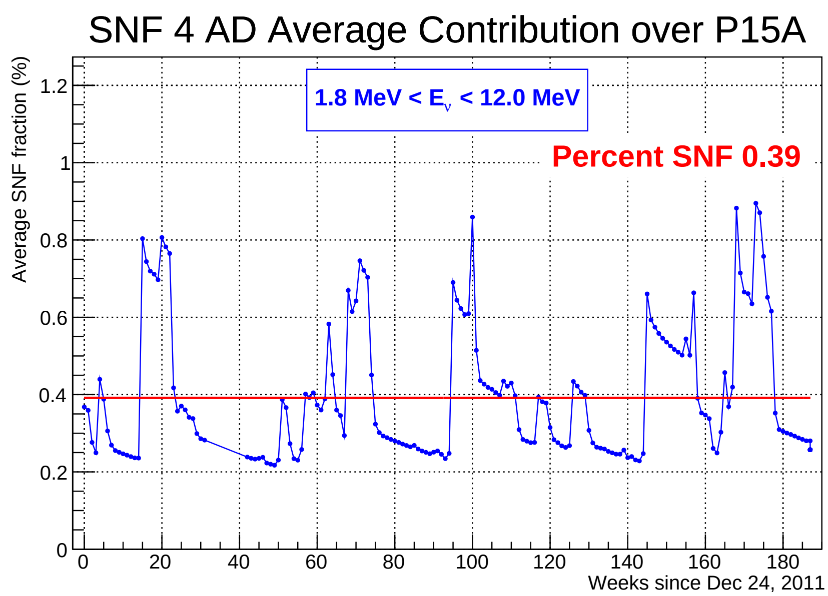

Figure 8: SNF fractional contribution averaged over each of the four near detectors and shown versus week in P15A.

5 Errors and uncertainties

Previous analyses of SNF have used ±100% relative error on the shape and ±50% on the total flux. This likely overstates the actual uncertainty but in the absence of suggested uncertainties in the calculation of the SNF spectrum in [12] I retain the same simple prescription. This includes uncertainty from the choice of burnup factor α_r. It is worthwhile, however, to investigate the effect of shifting some of the assumptions used in this analysis including the following:

- Refuel history: exclude fuel added to the SNF pools prior to P15A.
- Reactor off scaling: change reactor off scale factor.
- SNF pool positions: add uncertainty to positions of pools.

5.1 Inclusion of SNF added to pools prior to P15A

The inclusion of a history of addition of SNF to the reactor storage pools prior to P15A has a significant affect on the calculated result. Looking at the plots in Fig 7 shows that every time a reactor turns on after refueling, the SNF fraction instantly drops and then slowly decays back over 40-50 weeks to a nearly constant baseline or pedestal value of about 0.25%. This baseline is the nearly constant background expected from regularly refueling of the reactors. If a history of SNF prior to P15A is not included, you will get the wrong answer because this pedestal value is not included. In fact, what you see is that the baseline value slowly builds over P15A becoming about the 0.25% pedestal you expect by the end. This effect can be easily seen in Fig. 9. Inclusion of the refuel history moves the Detector 0 SNF result from 0.30% to 0.44%. Fig. 10 compares the SNF spectrum including and excluding refuel history.

To estimate the size of the uncertainty associated with the periodic refuel history prior to P15A, I ran 100 trials where I randomly varied the refuel times by ±20% of the assumed refuel period for each reactor. The results of these trials can be seen in Fig 11. The standard deviation of the trial calculations for each energy is approximately proportional to the value of the spectrum giving a relative standard deviation of <4%, negligible in comparison with the 50% relative uncertainty assigned to the SNF flux calculation.

5.2 Reactor off scaling

The SNF fraction is enhanced by a factor of 2.0 when the reactor is off to account for the effect that the entire reactor core is behaving as "effective" SNF. Once the reactor turns back on, the fuel in the core starts burning again and is no longer acting as SNF while the 1/3 removed continues decaying in the pool. The effect of the factor of 2 enhancement while the reactor is on can be seen in Fig. 12.

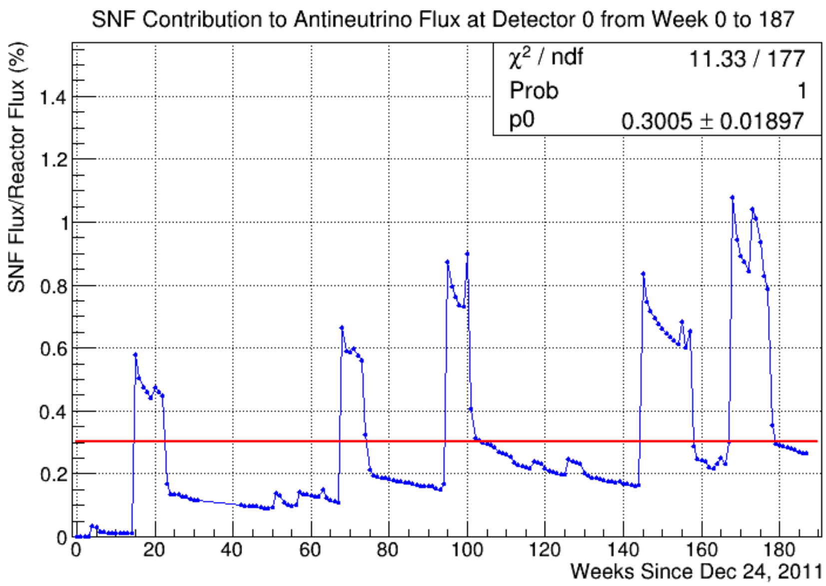

Figure 9: Calculated fractional SNF contribution to Detector 0 including no history of SNF prior to P15A. Compare this with Detector 0 in Fig 7 and notice the baseline slowly build up until it is nearly the same by the end of P15A.

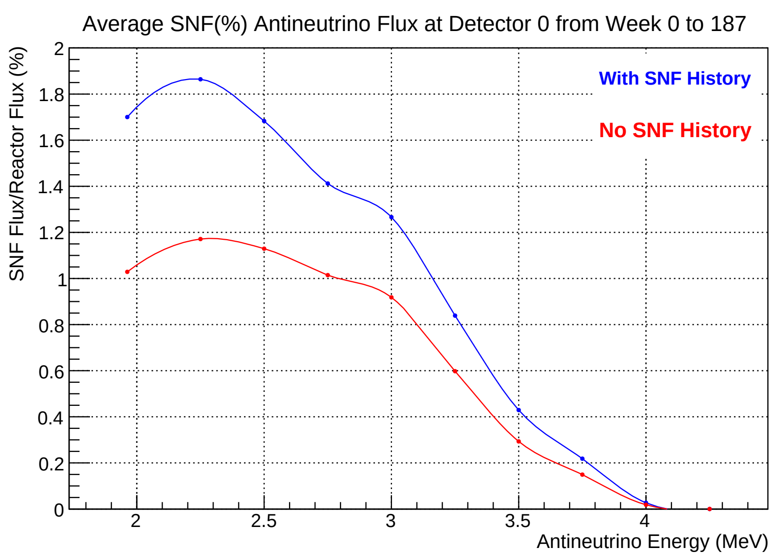

Figure 10: Calculated fractional SNF spectrum for Detector 0 showing effect of including SNF build up in the pools prior to P15A. The curve connecting the data points is a cubic spline and not part of the calculation.

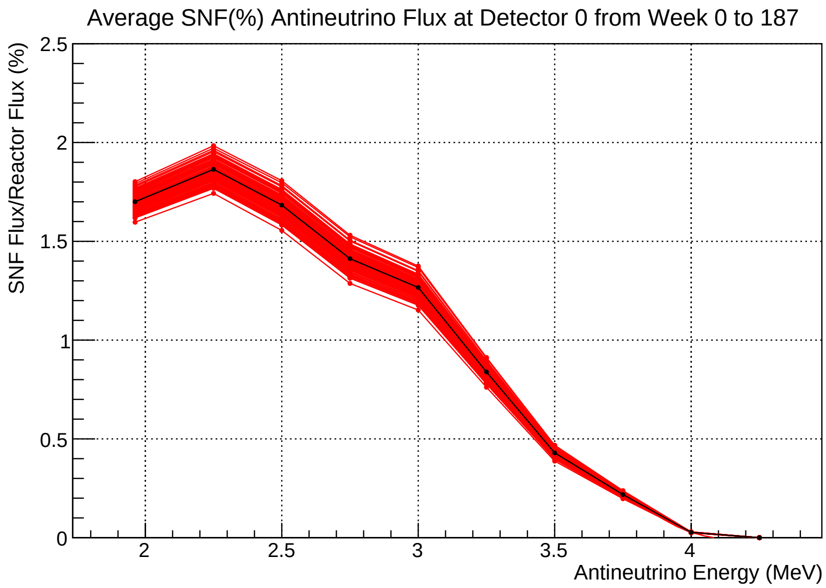

Figure 11: 100 trial SNF spectra for Detector 0 where the times between refuels prior to P15A were randomly varied by a number from a normal distribution centered on 0 and with a sigma of 20% of the assumed refuel period for each reactor. Black shows the calculation with the assumed regular periodic refueling.

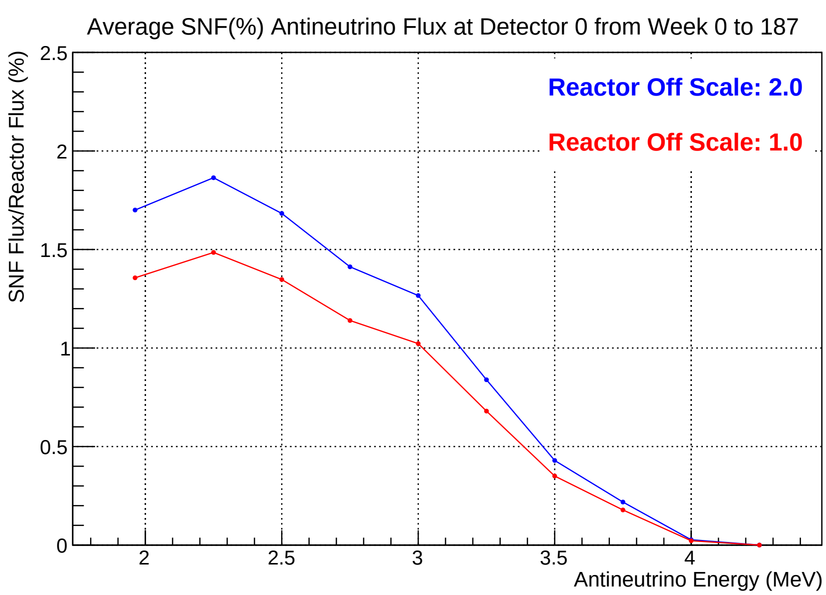

Figure 12: Plots shown comparing the results of including the factor of 2 scaling factor for reactor off periods.

5.3 Effect of changing SNF pool locations

Although the position of the SNF pools is well-known from survey [4], the pools have a finite size. The effect of randomly varying the pool positions by ± 15 m ($1\ \sigma$) in both the x and y directions was investigated and found to contribute a relative uncertainty of $<6\%$. This is small compared to the 50% relative uncertainty assigned to the flux calculation.

An earlier analysis performed by C. Lewis assumed that the SNF pools were located at the same position as the reactor cores which adds a systematic shift of the pools away from the detectors. A systematic shift like this has the potential to create a non-negligible change in the result. For example, using the assumption that the SNF pools are located at the same position of the reactor cores reduces the average expected SNF contribution to the near detectors from 0.39% to 0.35%.

Note that in my analysis the factor of 2 reactor off scaling treats the entire core as SNF, but its position is considered to be at the SNF pool location. In reality, during refueling about half the SNF flux comes from fuel moved to the pools and half comes from the core. The cores and pools are located about 80 m apart. However, the total reactor off scaling introduces a $\sim$20% shift and locating the SNF pools at the position of the reactor cores shifts the result by $\sim$4%, so a 4% shift of a 20% relative effect is less than 1% which is negligible compared with the 50% relative uncertainty assigned.

6 Conclusions

The fractional IBD flux and spectrum of SNF in the four Daya Bay near hall detectors has been calculated. The SNF spectrum is largest at low energies and quickly drops to 0 above 4 MeV. The total expected SNF contribution to the IBD signal is $0.39\pm0.20\%$.

[4]The Daya Bay reactor SNF pools were not known from survey although the reactors were. Contacts from the power company assured the survey group that due to the similarity of the reactor designs with the other four reactors, these could be determined relative to the reactor cores using relative offsets determined from Ling Ao reactors [6].

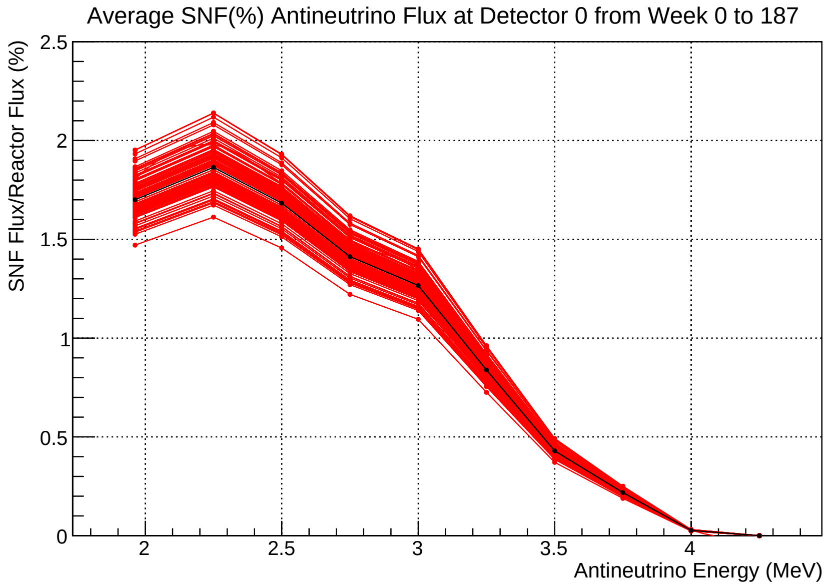

Figure 13: Result of calculated 100 trial SNF spectra for Detector 0 shown with the position of the SNF pools randomly varied in x (North/South) and y (East/West) by ± 15 m. The relative standard deviation of the trials is $<6\%$. The black curve is calculated at the position of the SNF pool center.

References

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