PP25: A Double Beta Decay Experiment
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## Abstract

A study into position reconstruction is presented for the neutrinoless double beta decay experiment SNO+ (Sudbury Neutrino Observatory). A simple Monte Carlo simulation of SNO+ is presented and compared to an existing complex simulation. A position reconstruction algorithm is shown to lead to a resolution of 38cm in a complex simulation of SNO+ and 4cm in the simple simulation. An algorithm to determine multiple decays within the triggering window (pileup events) is presented. This is shown to discriminate two equal energy events separated by 50cm when simulated in the simple SNO+ simulation. The implications of this for background rejection in SNO+ are discussed.


# 1 Introduction

The aim of the SNO+ experiment is to study double beta decay, to search for neutrinoless beta decay ($0\nu2\beta$).

The SNO+ detector will consist of an inner acrylic vessel (AV) (radius 6m) filled with Neodinium (Nd) loaded scintillator. Surrounding the AV will be water within which there will be the PMT (PhotoMultiplier Tube) array at radius 8m. All of which will be located deep underground in the old SNO Cavity.

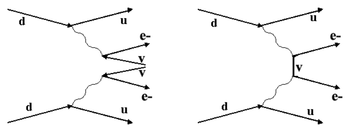
The placement deep underground reduces the cosmic muon background radiation. The large size of the AV allows better sensitivity as the sensitivity for the $0\nu2\beta$ lifetime is $\propto \sqrt{Mt/\Delta EB}$[14] where M is the mass of the AV content, t the measuring time, $\Delta E$ is the energy resolution of the detector and B is the background.

Double beta decays usually occur with the emission of two neutrinos (figure 1(a)), however if the neutrino were to be a Majorana[1] particle it could be possible for a double beta decay to occur without emitting neutrinos (figure 1(b)).

If neutrinoless double beta decay were possible, the rate of this double beta decay would be proportional to the effective[2] neutrino mass squared[2].

[1] Anti-particle is identical to the particle for Majorana particles.

[2] Effective mass due to neutrino oscillations



(a) Normal ($2\nu2\beta$) (b) Neutrino Less ($0\nu2\beta$)

Figure 1: Feynman diagrams for Double Beta Decay(a) and neutrinoless (b)

The isotope $^{150}$Nd has the potential to double beta decay and thus neutrinoless double beta decay. For Nd loaded in the AV the expected energy spectrum would be as shown in figure 2. The figure shows the normal double beta decay spectrum in orange with an end point around 3.5 MeV where the neutrinoless double beta decay (grey) spectrum is located. The total spectrum then has a slight shoulder at this end point energy indicating that neutrinoless double beta decay has occurred. The neutrino would then be known to be Majorana and the mass would be determined by the rate of the decay. The other spectra shown are due to the expected background, which is mainly due to the presence of nuclei in the naturally occurring radioactive decay chains of $^{238}$U and $^{232}$Th.

These background events are minimised by the use of purification techniques to reduce the

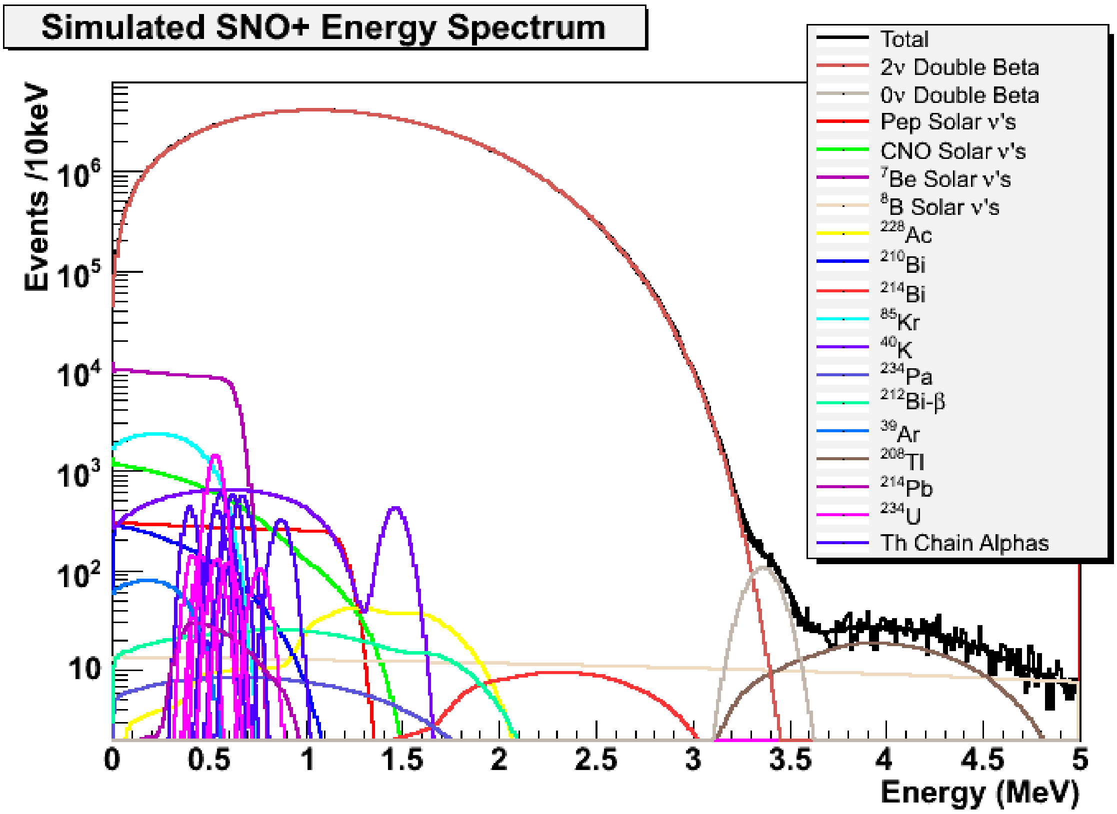



Figure 2: Energy spectrum if the effective neutrino mass is assumed to be around 150mev. Taken from the SNO+ website[10]

radioactive contaminants. Further background reduction can be carried out by rejecting any events that take place near the edge of the AV which arise from radioactivity in the surrounding water and PMTs. For the neutrino double beta decay experiment the background in the double beta decay end point energy region for $^{150}$Nd, must be reduced.

If multiple background decays occur within the triggering window (the time between a trigger[3] and 300ns after) it is possible for the total energy deposited to fall into the end point range i.e. around 3.5 MeV. These multiple decays occurring within the triggering window (pileup events) have the capacity to cause problems in the analysis, by obscuring the shoulder associated with any $0\nu2\beta$ decays.

In SNO+, pileup events are likely to cause errors in the analysis if no action is taken, especially if natural Nd is used, as opposed to Nd enriched in $^{150}$Nd[3]. A pileup event multiplicity of 1 (2 decays within the triggering window) is the most likely[3].

The purpose of this project is to develop methods useful in identifying the background and pileup events. For background events the main effort will be to look at the reconstructed position and reject events near the AV. For pileup events an algorithm will be developed to distinguish these from normal events.

## 2 Experimental Equipment

Two simulations of SNO+ are used in this project. The first, RAT (Reactor Analysis Tools), was developed by the Braidwood Collaboration, the second, MC (Monte Carlo Sim-

[3] Many PMTs being hit within a few nanoseconds

ulation), has been developed by myself for this project. RAT is a complex simulation of SNO+ whereas the project simulation MC is designed to be used as a proof of principle tool.

RAT is a Monte Carlo simulation of a liquid scintillator detector surrounded by PMTs[1]. RAT is an object orientated C++ system that builds on the Geant4[6] particle simulation code and the GLG4[8] scintillation and optical code. RAT adds the detector geometry, data acquisition and processing (DAQ) and event processing control.

The installation of RAT presented problems as some of the install commands were missing from the documentation and extra commands were required to run on the Scientific Linux 4 systems (SL4)[4]. The full list of commands that I found were needed to install RAT are given in Appendix A.

The project developed simulation MC is a Monte Carlo simulation of a liquid scintillator detector surrounded by PMTs but with the following simplifications:

- The geometry is limited to a constant filled volume of liquid scintillator up to the PMT Positions
- The scintillator is limited to a constant photon number yield per MeV of the exciting charged particle energy, with each emitted photon having the same frequency
- The scintillator has a defined emission time waveform
- When each PMT registers a hit the time is recorded without error and the charge recorded is subject to a Gaussian spread
- There is no absorption or remission of light in the scintillator
- The decay particle is modeled as static

The MC code is written in C++ in an object oriented manner. The installation instructions are given in Appendix B.

[4]RAT is not compatible with Microsoft Windows or SL3

# 3 MC, RAT Comparison

For the MC simulation to be used to investigate the best case results possible in RAT (and thus SNO+) it is necessary to ensure that the two give comparable output for the same event. This was checked by analysing the time distribution and the charge distribution recorded by the PMTs for comparable events i.e. decays of the same energy, location and particle.

The first check was to compare the number of hits for beta decay of a 5 MeV electron, which will give an indication of the accuracy of the MC scintillator photon yield and of the geometry in MC.

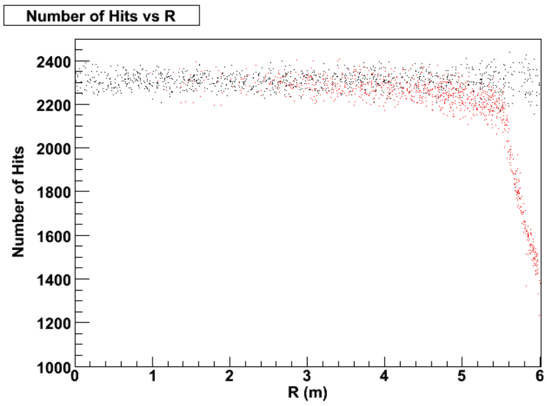
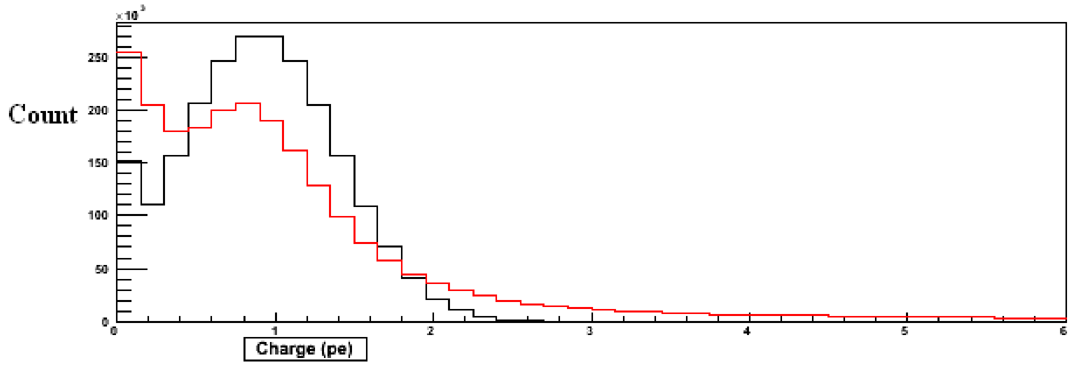



Figure 3: The black points correspond to the MC values, and the red to the RAT Values. The sharp drop in RAT as $r \approx 6m$ is believed to be due to the MC not modelling the AV and surrounding water

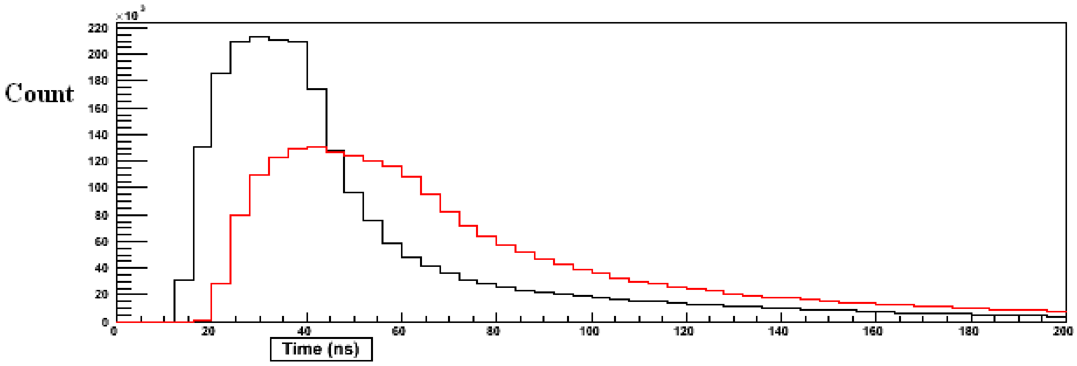
From inspection of the output heprep[12], visualisation files it was determined that the geometry is correct in MC (see Appendix C for an example file).

The number of hits at $r = 0$ gives an indication of the photon yield. The total solid angle of the PMTs as a fraction of the full spherical surface at $r = 8m$ times by the photon yield for 5 MeV is equal to the number of hits. This gives the photon yield as $\approx 4000$ photons for 5 MeV or 800 photons per MeV, which is consistent with RAT (see figure 3).

The charge and time distributions in MC were compared with those in RAT as shown




(a) The Peak in the charge corresponds to the mean charge (the distribution is Gaussian, the high count as $Q \to 0$ are from hits generating no charge being counted (in MC and RAT) and noise (only in RAT))




(b) The rise and fall shape is not due to the scintillator but rather the event being offset to $|r| = 4m$. The peak therefore corresponds to the mean time to hit the further away PMTs. The RAT histogram has a later first hit time and later peak as the refractive index of the medium is higher in RAT than in MC. Finally the lower peak in the RAT histogram is due to absorption and re-emission effects as these will tend to increase the width of the distribution hence lowing the count.

Figure 4: The black histogram corresponds to the MC values, and the red to the RAT Values. These are from beta decay of a 5 MeV electron at $|r| = 4m$.

in figure 4. As can be seen and is explained in the caption the MC distributions reproduce the key aspects of those in RAT.

# 4 Charge Centroid Fitting

The charge centroid position reconstruction method is the default in RAT and uses the charge information on the PMTs only. This technique relies on closer PMTs receiving more photon hits.

The charge generated on a PMT is proportional to the number of photon hits and the number of photo electrons per hit. The probability of a photo electron being generated is dependent on the frequency of the incident photon. In MC the photon frequency is constant whereas in RAT there is a spectrum of frequencies.

The charge centroid fit uses the following formula to compute the location of the event:

$$\mathbf{x}' = \frac{\sum_{i=0}^{N}(\mathbf{P}_i Q_i^f)}{\sum_{i=0}^{N} Q_i^f} \tag{1}$$

Where $\mathbf{P_i}$ is the PMT position, $Q_i$ is the PMT charge, $N$ is the number of PMTs, $f$ is the Fitting Power[5] and $\mathbf{x}'$ is the fitted position.

[5] Usually $f = 2$

The expected error can be ascertained by considering the charge distribution of the PMTs for a decay at $\mathbf{x}$. The charge distribution is found by considering the fractional solid angle ($S_i$) for each PMT, which in the approximation $|\mathbf{P_i}-\mathbf{x}|$ is large in comparison with $\sqrt{A}$ (square root of the PMT Area), is:

$$S_i \approx \frac{A \cdot cos(\delta)}{(\mathbf{P_i}-\mathbf{x})^2} \tag{2}$$

Where $cos(\delta) = \mathbf{P_i} \cdot \mathbf{x}/(|\mathbf{P_i}||\mathbf{x}|)$.

Provided a PMT receives many photon hits then the charge $Q_i$ is proportional to $S_i$ and $\mathbf{x}'$ can be estimated by substituting $Q_i$ for $S_i$ in equation 1.

Beta decays are simulated randomly throughout the AV in MC, at high energies[6] to ensure that the charge distribution in the theory is approximated in the results, each PMT receives multiple hits. The results are shown in figure 5. These clearly show that the theory (the solid angle approach) provides an understanding of the observed error.

The charge centroid position reconstruction method is fundamentally flawed as even the best case theoretical result (shown in figure 5) does not lead to a resolution of 0 cm. It is however a quick[7] method in terms of CPU time for getting an approximate location of the event which can then be used as a seed for more accurate but slower methods.

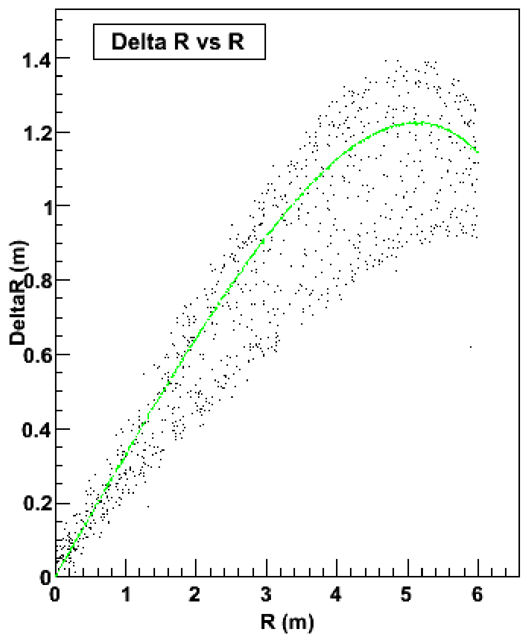



Figure 5: Delta R ( $|\mathbf{x}' - \mathbf{x}|$ ) Vs r for a charge centroid fitting of 50 MeV electron randomly placed throughout the av. Black Simulated, Green Theoretical for f=2. The spread in the Delta R values is due to the relatively low occupancy at the simulated energy of 50 MeV

# 5 Time Chi Squared Fitting

The time chi squared reconstruction method relies on a single hit being related to the distance to the event from the PMT. However this is limited by an uncertainty caused by the scintillator emission time.

To simplify the investigation into position reconstruction and pileup, the origin of time was taken to be the time of the decay.

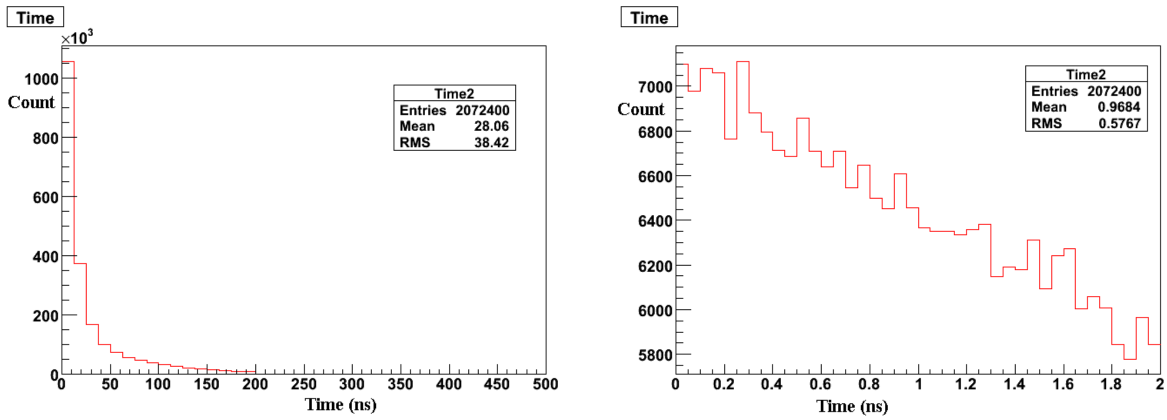
In terms of timing the scintillator in the MC simulation simply delays the emission of photons. In the RAT simulation it also absorbs and re-emits photons further delaying the photon. Note that the scintillator in RAT also changes the frequency of the photon thus changing the charge on the PMT, but this causes no problems for the time chi squared reconstruction method.

The scintillator is based on Gd loaded scintillator originally used in KamLand[11]. SNO+ will use LAB (linear alkyl benzene). The parametrised properties of LAB are not known at the time of writing but it is expected to be similar to Gd loaded scintillator.

The decay waveforms shown in figure 6 are typical for all scintillators. The delay in emission is always positive and the emission probability peaks around 0 and falls exponentially. Between 0 and 2 ns the mean delay time caused

[6] $\approx$ 50MeV

[7] Compared against the Time Chi Method




(a) Decay Waveform histogram

(b) Decay Waveform histogram for times between 0ns and 2ns (2ns is referred to as the cut off time)

Figure 6: Gd Loaded Scintillator decay waveform properties

by the scintillator is very close to half the cut off time i.e 1n in figure 6 (mean is 0.9684 with a 2ns cut off time).

The Chi Squared Minimisation method is used to fit a function $f(x:\beta)$ to data $y(x)$, where $x$ is the domain over which the function and data are valid and $\beta$ are the fitting parameters. The fitting parameters $\beta$ are chosen such that the sum of the residuals $r_i$ squared is minimised. The residual is the difference in the fitted value to the data value.

$$\chi^2 = \frac{\sum_{i=0}^{N} r_i^2}{\sigma^2} \quad (3)$$

$$r_i = (y_i(x) - f_i(x:\beta)) \quad (4)$$

Where $\sigma$ is the standard deviation of the error on $y(x)$. Assuming $f(x:\beta)$ is chosen such that (for the best fit):

$$y_i(x) = f_i(x:\beta) + \epsilon_i \quad (5)$$

Where $\epsilon_i$ is the error on $y_i(x)$. The residual $r_i = \epsilon_i$ and hence:

$$\chi^2 = \frac{\sum_{i=0}^{N} \epsilon_i^2}{\sigma^2} \quad (6)$$

$$= \frac{\sigma^2 N + \mu^2 N}{\sigma^2} \quad (7)$$

Where $\mu$ and $\sigma$ are the mean and standard deviation of the error distribution $\epsilon_i$. For normally distributed errors in which $\mu = 0$ the minimum value for $\chi^2$ is $N$.

The errors on the parameters $\beta$ from the chi squared fit is defined by the change in the parameter which causes the $\chi^2$ function to vary by one when all other parameters are optimised[15].

In MC and RAT: $i$ runs over all the PMTs, $y_i(x)$ is $t_i$ the recorded PMT hit time, and $f(x:\beta)$ is $t_{theory,i}(\beta)$. The statistical error distribution $\epsilon_i$ in SNO+ has a $\mu \neq 0$. Hence all times are delayed on average $\mu$. As $t_{theory,i}$ is the expected time between the event occurring and a photon hitting PMT i, $t_{theory,i} = t_{flight,i}(\beta) + \mu$ where $t_{flight,i}(\beta)$ is the time taken for a photon to travel from the event to the PMT $i$. Hence the chi squared equation is:

$$\chi^2 = \frac{\sum_{i=0}^{N}(t_i - t_{theory,i}(\beta))^2}{\sigma^2} \quad (8)$$

$$= \frac{\sum_{i=0}^{N}(\epsilon_i - \mu)^2}{\sigma^2} \quad (9)$$

$$= \frac{\sigma^2 N + \mu^2 N + \mu^2 N - 2\mu^2 N}{\sigma^2} \quad (10)$$

$$= N \quad (11)$$

However this method gave incorrect fitting parameters $\beta$ as the method assumes that the error distribution $\epsilon_i$ is Gaussian, whereas in SNO+ it is an approximate exponential decay with $\epsilon_i > 0$ as shown in figure 6.

The solution to this problem, found empirically, is to increase the value $\alpha$ in $t_{theory,i} =$

$t_{flight,i} + \alpha\mu$ to a large positive number. This was tested in the MC simulation and the results for different values of $\alpha$ are shown in table 1.

| $\alpha$ | Mean Resolution (m) |
|---|---|
| 1 | 3.391 |
| 2 | 0.3612 |
| 3 | 0.281 |
| 4 | 0.2741 |
| 6 | 0.262 |

Table 1: $\alpha$ values and the typical resolution from simulations in MC. Further work is needed to understand this dependence on $\alpha$.

It is now possible to write a chi squared equation for use in SNO+:

$$\chi^2 = \frac{\sum_{i=0}^{N} r_i^2}{\sigma^2} \quad (12)$$

$$r_i = (t_i - t_{flight,i}(\beta) - \alpha\mu) \quad (13)$$

In this project the value of $\alpha$ used was 2 for the MC simulation and 20 for the RAT simulation. For further work a value of 6 or greater should be used for MC and 20 or more for RAT. A much larger value is required for RAT presumably because the time distribution is more spread out (see figure 4) due to absorption and re-emission.

The flight time is calculated by:

$$t_{flight,i}(\beta) = \frac{\sqrt{(P_{i,x}-\beta_1)^2 + (P_{i,y}-\beta_2)^2 + (P_{i,z}-\beta_3)^2}}{c/n} \quad (14)$$

Where n is the refractive index of the medium (assumed constant throughout) and c is the speed of light.

The algorithm used to reconstruct the position is:

1. Minimise $\chi^2$ using Minuit[9], 1st pass.
2. Exclude PMTs that fail

$$t_i - t_{flight,i}(\beta_{FirstPass}) < t_{Cutoff} \quad (15)$$

   Where $\beta_{FirstPass}$ is the fitted position from the first minimisation, and $t_{Cutoff}$ is the error magnitude from the first minimisation divided by the speed of light in the AV, typically 2ns.
3. Minimise $\chi^2$ with the remaining PMTs only, 2nd pass.

The second pass only uses the least delayed photons i.e. the ones that more closely equal the flight times. This is done to reduce the effect the scintillator delay and the absorption and re-emission delay have on the position determination.

There is difficulty in knowing the theoretical $\mu$ of the time distribution in SNO+ as it is also dependent on geometric effects and on the scintillator absorption and re-emission properties. This was solved by calculating $\mu$ for each reconstruction.

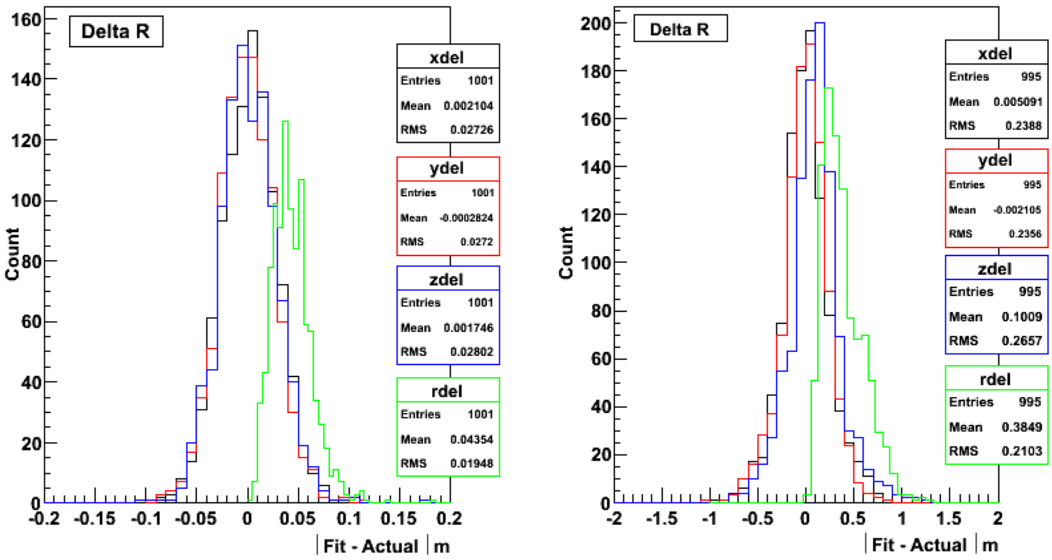
The calculation of the mean is done by letting the mean in chi squared equation be a variable $\mu_c$:

$$\chi^2 = \sum_{i=0}^{N} (t_i - t_{flight,i}(\beta) + \mu_c)^2 \quad (16)$$

While the fitted position is poor the value of $\mu_c$ is fairly accurate (as shown later in figure 8(a)), however exact values are not needed as $\alpha$ is typically a large number.

In the simple MC simulation the reconstruction algorithm gave an average resolution of ≈17cm from the first pass minimisation and then ≈4cm from the second pass minimisation with no bias. See figure 7(a).

In the RAT simulation the reconstruction algorithm give an average resolution of ≈70cm from the first pass minimisation and then ≈38cm from the second pass minimisation. See figure 7(b). The reconstruction in RAT has a radial trend that gets much worse in the region $5 < r < 6m$. This is believed to be due to the refractive index in RAT not matching that used in the theoretical time calculation, and that the assumption that the refractive index is a constant throughout the detector is also not valid.




(a) MC Results

(b) RAT Results

Figure 7: Results from the time chi squared position reconstruction for beta decay of a 5 MeV electron occurring randomly throughout the AV. Each histogram shows the error in the Fit to actual i.e. | Fit - Actual |. Black is errors in x coordinate, Red is errors in y coordinate, Blue is errors in z coordinate and Green is the distance from the fit to the event location.

The chi squared position reconstruction resolution is dependent on the event energy, an increase in the event energy leads to a better fit as shown in table 2.

| Electron Energy (MeV) | Mean Resolution (m) |
|---|---|
| 5 | 0.04 |
| 3 | 0.06 |
| 1 | 0.12 |

Table 2: Typical fit resolution for different energy electrons simulated in MC.

## 6 Pile up determination

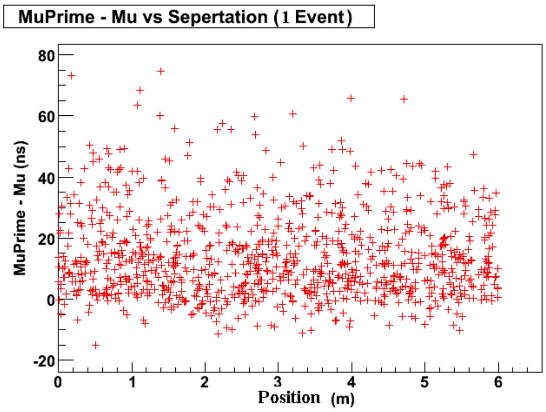
As mentioned in the introduction one of the main aims is to determine which events are pileup events. The method I developed in this project to determine pileup events uses the output of the time chi squared position reconstruction algorithm, this has the advantage of adding little extra computing time.

If the event is a pileup event (multiple decays in the triggering window), the $t_i$ (PMT time) can never equal $t_{flight,i}$ in the minimised state. As the fit will tend to be between the decays, hence even for the prompt photons $t_i \neq t_{flight,i}$. The effect of this additional variation in the PMT times $t_i$ is equivalent to an decrease in the effective mean delay time $\mu'$ i.e.$\mu' < \mu$ the change $\delta$ is identified by $\delta = \mu' - \mu$.

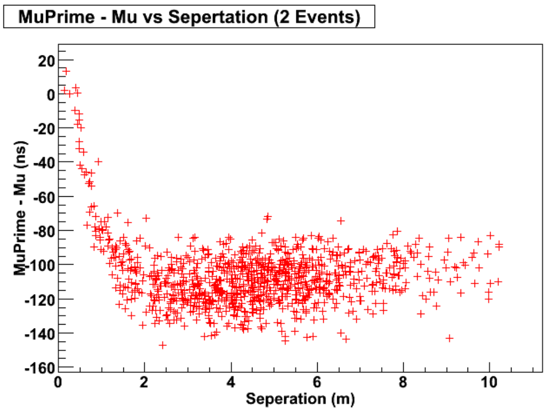
The value of $\mu'$ is calculated in the second pass minimisation[8]. As the time spectrum is cut to just use times between 0 and $t_{Cutoff}$ which is typically about 1 - 2 ns. This part of the scintillator spectrum (0 - 2ns) can be approximated by a distribution with $\mu = 0.5 * t_{Cutoff}$ (see figure 6).

The algorithm was simulated for a single decay in MC to establish the expected variation

[8] See time chi squared method




(a) Single Decay Event simulated in MC




(b) Two Equal Energy Decay Events simulated in MC

Figure 8: $\mu' - \mu$ for beta decay of 5MeV electrons randomly placed throughout the detector simulated in MC

in $\delta$, the results are shown in figure 8(a). The variation is large but, usefully, does not show any trends with the position. The algorithm was then simulated for two equal energy decays i.e. a pileup event. The results are shown in figure 8(b).

If $\delta < -20(ns)$ then the event can be easily attributed to a pileup event as opposed to variation in the single event value. This corresponds to a $\approx 50cm$ minimum separation.

For unequal energies it is expected that $|\delta|$ will decrease in value for the same separation as equal energies. This is because the fit can be made closer to the higher energy decay as the higher energy decay will cause more hits and thus dominate the residuals. The results for unequal energies is shown in figure 6.

Using the condition $\delta < -20(ns)$ then the unequal energy pileup (for 1.6 MeV and 3.2 MeV electrons) can be determined to a $\approx 80cm$ minimum separation.

The pileup determination method has not been tested in RAT. However if it is assumed that the RAT minimum separation is also 50 cm then the pile up count will be reduced by a factor of $0.5^3/6^3$ whilst if a minimum separation of 1 m corresponds to a factor of $1/6^3$.

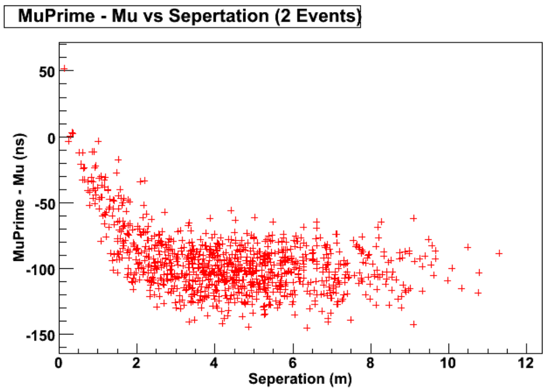



Figure 9: $\mu' - \mu$ for two unequal beta decays of 1.6MeV and 3.2MeV electrons randomly placed throughout the detector simulated in MC

# 7 Further Work

There are two assumptions used in the time chi squared reconstruction method that will need to be computed for accurate use in SNO+. The first is that the origin of time is implicitly assumed to be when the decay occurs. This would have to be determined in the fitting algorithm or relative times used. The second assumption is that the refractive index is a constant throughout SNO+, however SNO+ has regions of differing materials and thus has dif-

| Background | Normal Count | Pileup Reduced Count |
|---|---|---|
| $2\nu$ | 3 | $\approx 0$ |
| $^{144}$Nd | 265 | 1 |
| $^{14}$C | 418 | 2 |
| $^{85}$Kr/$^{39}$Ar | 60 | $\approx 0$ |
| $^{176}$Lu | 486 | 2 |
| $^{147}$Sm | 3982 | 18 |

Table 3: Number of pileup events that have an energy in the range 3.0 to 3.7 MeV from 3 years of running assuming 1 tonne of Nd[3]. Assuming reduction factor is $1/6^3$.

fering refractive indices.

The effect of the event energy on the resolution of the chi squared fit is not fully known. The results quoted for 5 MeV are of the correct magnitude for the expected events (see figure 2) and serve as a proof of principle, further work is required to quantify the resolution dependence on energy.

The pileup determination algorithm needs to be simulated in RAT. In RAT the extra delay caused by the absorption and re-emission will need to be investigated.

# 8 Conclusion

The MC simulation is a simpler and much quicker simulation for SNO+ (for example 1000 events in RAT takes $\approx$ 1.5 hrs, in MC $\approx$ 20 mins).

The achievable resolution in RAT of 38cm is, in comparison with the existing Charge Centroid algorithm, superior and at the time of writing only the Charge Centroid algorithm has been investigated in RAT for SNO+. However the KamLAND[11] experiment also uses a scintillator and the timing fitter developed by this group has a typical resolution of 25cm[13]. I believe the time chi squared method can match the 25cm value with the further work mentioned in section 7, or it could be used as a seed for a maximum likelihood method.

A minimum separation of 1m for pileup events will reduce the pileup count by a factor of $1/6^3$. A reduction factor of $1/6^3$ will reduce the pileup counts as in table 3. In comparison for an effective neutrino mass of 150 meV the neutrinoless double beta count is 280 for 3 years, the normal double beta count is 3000 events[4]. Whilst this leads to promising reductions, it does not take into account the decay energies, which may not be equal or in the ratio 2:1 as simulated in this project.

The pileup reduction method would be a significant addition to the SNO+ data analysis if it can be shown to give a similar minimum separation when simulated in RAT.

## References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[7] http://root.cern.ch/

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[15] http://seal.web.cern.ch/seal/documents/minuit/mnerror.pdf

# A RAT Install Instructions

The instructions are for SL4 bash shell machines.

```
Firstly download clhep 2.0.3.1, geant 4.8.2.p01 (inc. source files) from
http://proj-clhep.web.cern.ch/proj-clhep/DISTRIBUTION/clhep-1.9.html and
http://geant4.web.cern.ch/geant4/support/source_archive.shtml respectively.

Extract copy the clhep tar to folder $BASE, extract the clhep (tar -xzf
chlep...) then copy geant to a folder $BASE/geant4 and extract. (Technically
any folders are probably fine but need to define where they are for below:

All are bash shell ($), [] are for notes:
$cd $BASE/clhep-2.0.3.1 [or where ever clhep is extracted]
$./configure --prefix=$BASE/clhep [or anywhere you want to install it]
$make
$make check [not ness.]
$make install

$cd $BASE/geant4/geant4.8.2.p01
$./Configure build [Choose the install directory to be \ $BASE/geant4 or where
ever. Choose OPENGL y, ZLIB y, static lib y, and copy all headers]
$./Configure -install [not mentioned on geant step by step instructions]
$./Configure
$. env.sh

$cd $BASE
$svn co http://root.cern.ch/svn/root/tags/v5-14-00b root
$export ROOTSYS=$BASE/root
$cd \ $ROOTSYS
$./configure linux
$make
$make install

$cd $BASE
$export PATH=$ROOTSYS/bin:$PATH
$export LD_LIBRARY_PATH=$ROOTSYS/lib:$CLHEP_LIB_DIR:$LD_LIBRARY_PATH
$export PYTHONPATH=/usr/bin/python2.3 [Not usually set, not mentioned in RAT
install instructions]
$svn co http://nu.ph.utexas.edu/rat/svn/pub/rat
$cd rat
$./configure
$. env.sh
$scons [If this fails it is probably a python path issue esp. if the
scons.script file cannot be found]
```

# B Monte Carlo Install Instructions

The instructions are for SL4 bash shell machines. It is assumed that ROOT is installed( in a folder $ROOTSYS in these instructions, if it is not consult Appendix A

```
To compile place all the code file into a single folder (Code Files end in .cpp,
.hpp, .cc, .hh).
Then ensure the Library and include path for ROOT is setup:
export LD_LIBRARY_PATH=$ROOTSYS/lib:$LD_LIBRARY_PATH
export PATH=$ROOTSYS/bin:$PATH
Then compile:
g++ MCTest.cpp MCSimulateEvent.cpp MCDetector.cpp MCFitChiTime.cpp
MCTimeChiFit.cpp MCScint.cpp HepRepXMLWriter.cc -o MCTest -I$ROOTSYS/include
-L$ROOTSYS/lib -lCore -lCint -lRint -lPostscript -lMatrix -lPhysics -lHist
-lSpectrum -lpthread -lm -ldl -rdynamic -lMinuit -lMinuit2 -Wno-deprecated
Add the preprocessor definitions: -DDEBUG for detailed visulisation file,
-DQT for charge and time hit information file.
To run simple type:
./MCTest [Number of Decays per event] [Fit type] [Fit Parameter]
Where Fit Type can be 0:Centroid or 1:Time Chi Squared, and Fit Parameter
is the fitting power for the Centroid fit.
```

# C HepRep Output Example

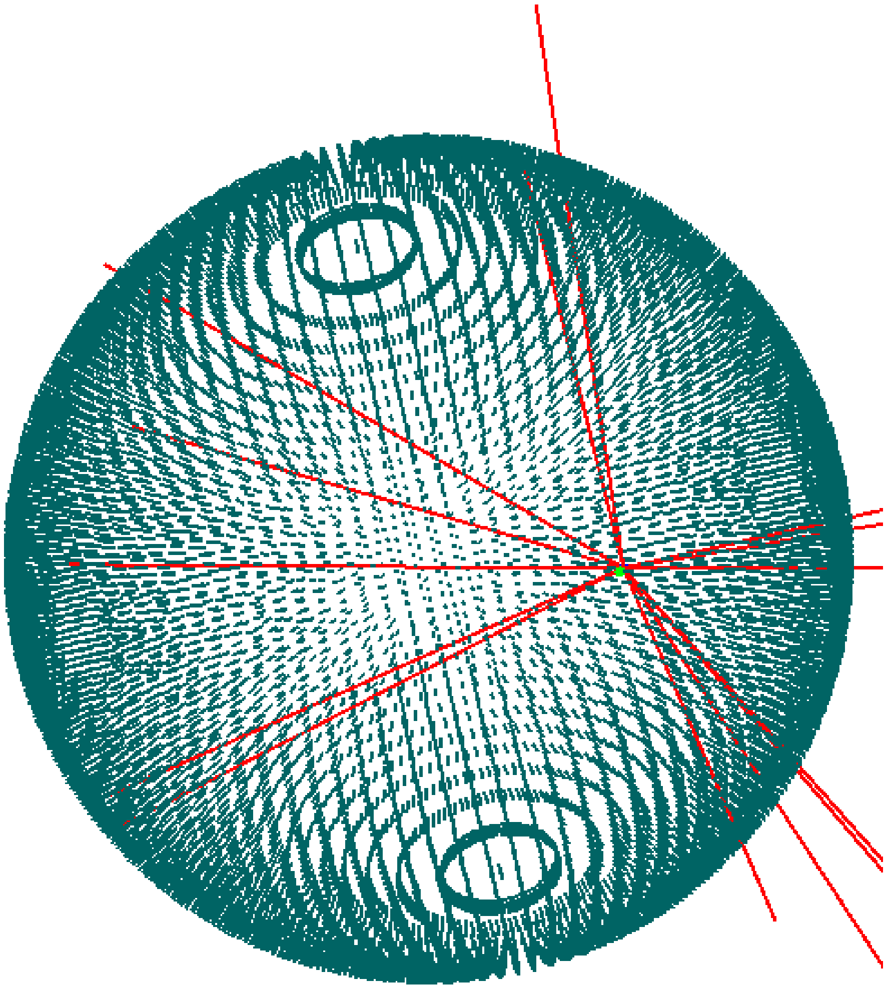

Figure 10: Example HepRep Event. The red lines are photon tracks, blue are PMTs, Green is the fitted position