Estimates of Inverse Beta Decay Mis-Identification in Braidwood

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September 6, 2005

At Braidwood, a measurement of θ_W can be made by counting $\bar{\nu_e}$ and ν_e elastic scattering (ES) events. Inverse Beta Decay (IBD) misidentification represents a significant potential source of error for the measurement of θ_W. We can estimate this error using one of the two methods proposed in reference [1]. In this note we study IBD misidentification using the first method proposed, with the ReactorFSim Monte Carlo.

1 Method

IBD misidentification (IBD Mis-ID) can occur in two ways. Either the positron or the neutron can be mistaken as an elastic scattering event if its partner is not seen. Out of 802780 reconstructed events 5178 IBD events had a neutron that was generated outside of the inner Gd-doped volume, while its positron was generated within the Gd-doped region. This is 0.6% of all IBD events. 15613 events, or 1.9% of IBD events enter the inner volume from outside. That is, their positron was generated in the outer mineral oil region, and its neutron was generated in the Gd-doped inner region. Thus, error from misidentified events is extremely significant. [1]

There are other backgrounds to the ES flux including contamination, spallation isotopes and secondary neutrons. The contaminant with the highest visible energy is ^{208}Tl, with an endpoint at 5 MeV. Because of this we limit our study to energies above 5 MeV. Thus, contamination is not a problem for this study. However, we must be sure that our studies are applicable for the 3-5 MeV energy range

In this Monte Carlo, secondary neutrons are negligible, Their energy is too low to be reconstructed. If secondary neutrons were to have higher energies, they could be reduced to a negligible level by ensuring no event occurred some time before the secondary neutron captured. The default Monte Carlo Gd concentration is 0.2 % Gd. This concentration gives one a neutron capture time for IBD events of 25 μs. Therefore a 0.21 ms window is suggested.

Spallation isotopes are produced by through-going muons and Mis-IDed when they interact in the Gd-doped inner region. We can eliminate most of these events by requiring a 0.1 s veto. The ReactorFsim Monte Carlo does not account for spallation isotopes, therefore they are not a background to the Monte Carlo IBD mis-ID rate.

In Ref. [1], IBD events where a neutron enters from outside of the inner volume were also treated as an error to the IBD Mis-ID rate. Such 'Orphan Neutrons' we now consider to be an

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[1] the discrepancy between these percentages and those in [1] are noteworthy. We do not know from whence they arise

additional factor in IBD Mis-IDs such that the total number of Mis-IDed events is the sum of the Orphans and the originally named IBD Mis-IDed events. To make the terminology simpler, the original IBD events are 'positron Mis-IDs' and the orphans are 'Neutron Mis-IDs'. Further studies with ReactorFsim also conclude that the 8 MeV Gd capture peak does not shift for 'Orphan Neutron' events, or events where neutrons enter the inner volume and the positron is in the mineral oil region. Figure 1 shows the reconstructed neutron energy for such events. The peak is clearly visible at 8 MeV

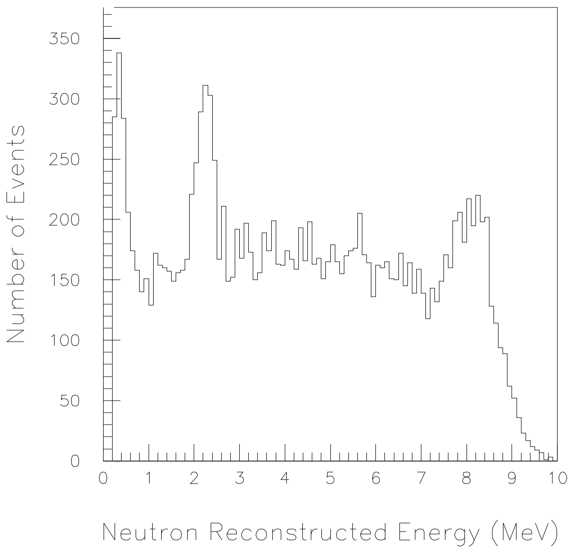


Figure 1: Total IBD events reconstructed where the neutron enters from outside and captures 15613 events

We can further break Mis-IDs down into eight categories, numbered according to where the neutron and positron are generated, and which one is reconstructed, as seen in Table 1.

Particle Seen		e^+	n
Vertex of e^+	Vertex of n		
$< 260cm$	$< 260cm$	Category 1	Category 2
$< 260cm$	$> 260cm$	Category 3	Category 4
$> 260cm$	$< 260cm$	Category 5	Category 6
$> 260cm$	$> 260cm$	Category 7	Category 8

Table 1: Category names for each kind of IBD mis-ID by generated vertex and misidentified particle..

The first column represents all events where the positron is seen and reconstructed within the fiducial volume. These are the positron Mis-IDs. The second column are all events where the neutron is seen and reconstructed within the fiducial volume. These are neutron Mis-IDs.

The total number of Mis-IDs is the sum of the table.

For our analysis we use the percentage of Monte Carlo predicted Mis-IDs as an estimate for the percentage of the background for the elastic scattering events. We determine this percentage by the following

$$\frac{N^{MC}_{misIDs}}{N^{MC}_{IBD}} = r \tag{1}$$

$$N^{data}_{misIDs} = r \times N^{data}_{IBD}$$

where N^{MC}_{misIDs} is the total number of Mis-IDed IBD events in the monte carlo,N^{MC}_{IBD} are the total number of well reconstructed IBD events in the Monte Carlo, N^{data}_{IBD} is the number of well reconstructed IBD events in the data and N^{data}_{misIDs} is the predicted number of background Mis-ID events for the data.

2 Errors

The error on each category, as well as the total number of mis-IDs or IBDs for the Monte Carlo is found by using $\sigma_N = \sqrt{N}$ where σ_N is the error on the number of events N. We find, the error on the number of mis-IDs in the data, N^{data}_{misIDs}, is given by

$$(\delta N^{data}_{misIDs}) = \sqrt{\delta(r)}^2 + \delta(N^{data}_{IBD})^2 \tag{2}$$

and therefore

$$(\frac{\delta r}{r})^2 = (\frac{\delta N^{MC}_{misIDs}}{N^{MC}_{misIDs}})^2 + (\frac{\delta N^{MC}_{IBD}}{N^{MC}_{IBD}})^2 + (\frac{\delta r_{syst}}{r})^2 = \frac{1}{N^{MC}_{misIDs}} + \frac{1}{N^{MC}_{IBD}} + (\frac{\delta r_{syst}}{r})^2 \tag{3}$$

The first two terms are the statistical errors of the Monte Carlo samples and the third term is the systematic error on r due to uncertainties in the Monte Carlo modeling of the detector. Understanding the detector will help us minimize this.

3 ReactorFsim

ReactorFsim has characteristics that require further note. There is a threshold on the reconstructed positron and neutron energies of 0.2 MeV. This requirement means that if the reconstructed positron energy is less than 0.2 MeV, the positron is not reconstructed, and the Monte Carlo continues searching for a ‘positron’. Therefore, if the neutron reconstructs in an event where the positron is unseen, its energy deposition will be classified as a positron. This will result in an apparent increase of Positron Mis-IDs and a decrease in Neutron Mis-IDs. The total number of Mis-IDs, however, should remain unchanged.

For such ‘mislabled’ Mis-IDed events, we can compare the reconstructed energies to the simulated energy variables calculated by the smearing and vertex reconstruction of the particles. These simulated variables contain no advanced reconstruction and are bound to the identity of the particle that deposits the energy- they can not be mislabled.

Imposing that the simulated positron energy must be less than 0.2 MeV for positron Mis-IDs gives one roughly the number of mislabled Neutron Mis-IDed events. We find with this cut that out of 802780 reconstructed events, there are 13545 mislabled Mis-IDed events for all energies,

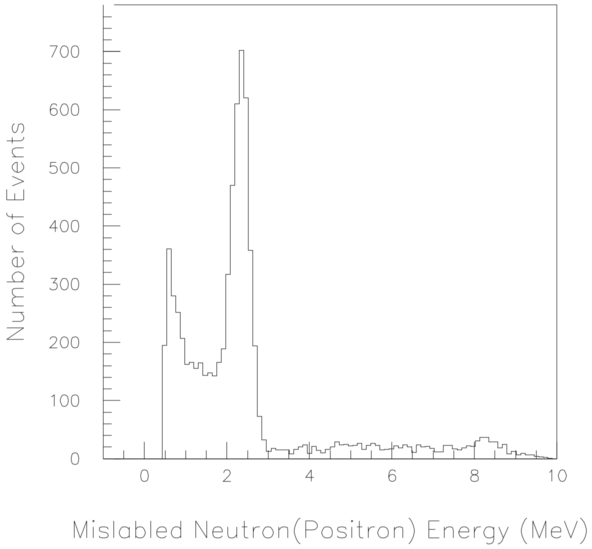


Figure 2: Mislabled Neutron Mis-ID events. 5640 total events. 803 Events between 5 and 10 MeV

and 803 mislabled events between 5 and 10 MeV. One can also identify the 2.2 MeV neutron capture peak, when these events are isolated (see Figure 2). The 8 MeV peak is very small, which suggests that neutrons that capture in the 8 MeV peak are generally preceeded by a visible positron.

Most of these mis-labled Mis-IDed events occur between categories 5 and 6, where the positron is in the outer mineral oil volume and the neutron is in the Gd-doped inner volume. This is reasonable, as it would explain why the positron reconstructed with less than 0.2 MeV in energy, and the neutron was mistaken as a positron. Subtracting these events from category 5, where they were misplaced and adding them to category 6, where they should have been, almost doubles the number of category 6 events and vastly minimizing the number of events in category 5.

If neither the positron or the neutron are seen, the event is not reconstructed. We find for 1196200 generated events 393420 events are not reconstructed, leaving 802780 reconstructed events. Figures 3 and 4 show the neutron and positron generted vertices respectively for unreconstructed events. We find that nearly all are in the undoped mineral oil region.The spike at 350 cm in Figure 3 is because we stop the neutron at the steel vessel.

Furthermore, alterations were made to the timing of the neutron capture, such that the number of events vs. the time difference between when the positron and neutron deposit energy is not completely exponential; a cutoff of 500 elastic scatters for the neutron was made in the Monte Carlo to save processing time. There is a small peak at 800000 ns due to this, as seen in Figure5. This should not affect our study.

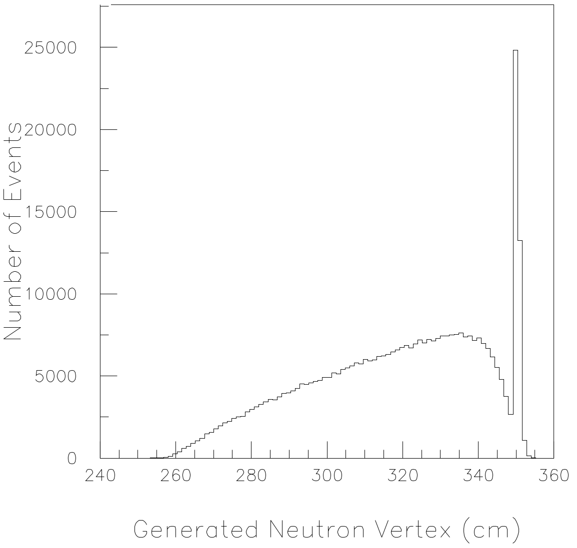


Figure 3: Generated neutron vertex for unreconstructed events. 393420 events

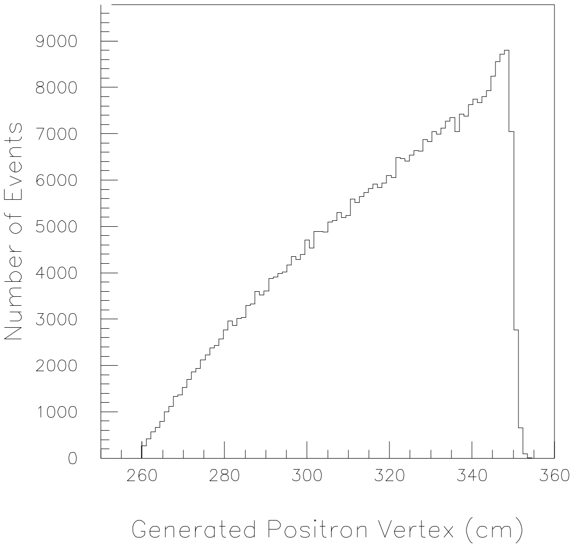


Figure 4: Generated positron vertex for unreconstructed events. 393420 events

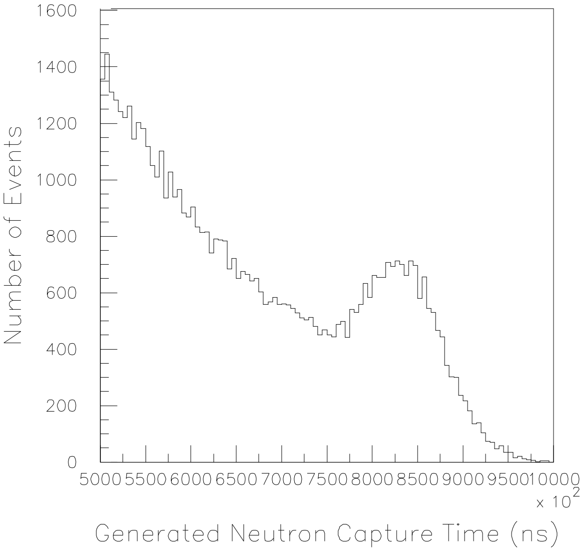


Figure 5: Generated neutron capture time. 59276 events shown

4 Analysis

A fiducial cut at 230 cm is proposed for the elastic scattering analysis in Braidwood. Because of spallation isotopes, a 200000 ns veto window can be introduced as well. There is reason to believe we should extend this veto window, as there are many IBD events with neutron capture time greater than 200000 seconds.

4.1 Well Reconstructed IBD events in the Monte Carlo

We require that well reconstructed IBD events have reconstructed positron energy greater than 0.5 MeV and reconstructed neutron energy greater than 6 MeV. Both the positron and neutron must reconstruct within the fiducial volume.

With a fiducial radius cut of 230 cm, there are 41923 well reconstructed IBD events without a timing veto window. There are 41922 events, just 1 less event, if the 200000 ns veto window is introduced. If we move the vertex cut to 260 cm, the edge of the acrylic vessel, there are 50003 reconstructed IBD events that pass all cuts, and 16 less events if a timing window is introduced.

4.2 IBD Mis-IDs in the Monte Carlo

Studies found that when the positron reconstructed energy was greater than 10 MeV, it had a 95 ± 21% likelihood of being Mis-IDed. The statistics on this are rather low. This effect is most likely caused by the neutron capturing so quickly after positron annihilation that the neutron energy is reconstructed with the positron. Another possibility, is that these events are due to Neutron IBD Mis-ID events with an unreconstructed positron. Because no positron was reconstructed the Monte Carlo Mis-Identified the neutron as a positron. Because of this, we further limited our studies to energies between 5 and 10 MeV.

The total number of Mis-IDed events for each category, out of 802780 reconstructed events is in Table 2 shown below.

Particle Seen	→	e^+	n
Vertex of e^+	Vertex of n		
< 260	< 260	308	48
< 260	> 260	38	0
> 260	< 260	962	890
> 260	> 260	73	24

Table 2: IBD Mis-IDs by positron and neutron generated vertex and Mis-Identified particle

The total number of Mis-IDed events is 2343 ±48, and the fraction of mis-IDs to well reconstructed IBD events is 0.056 ± 0.0012 . The values in each category are without any additional subtractions or additions due to mislabling- the 803 ±28 mislabled events have not been not subtracted from category 5 and added to category 6.

In the above analysis, a particle is considered ‘unseen’ if its reconstructed energy is less than 0.5 MeV. It is not reconstructed unless its energy is greater than 0.2 MeV. Because of this threshold, we can not limit our studies of the Neutron Mis-IDs to positrons with less than 0.2 MeV, because they are not reconstructed, however the Positron Mis-ID rate can be reduced if lower the ‘unseen’ reconstructed energy limit to 0.2 for neutrons -we exclude *any* event with a reconstructible energy deposition after the positron capture. With this cut, the number of Positron Mis-IDs is reduced from 1381 to 1297 events. the value of r in this case decreases to 0.053 ± 0.0012, however it is within two σ of our estimated total number.

4.2.1 Mis-IDs by Fiducial Radius

Mis-IDed events can also be analyzed by studying the effect of changing the fiducial radius. The number of total IBD Mis-IDs, reconstructed IBDs , and number of IBD Mis-IDs to reconstructed IBDs are shown below in Figure 6 as a function of the fiducial radius cut. As expected, these values increase when the fiducial volume is extended. When no fiducial cut is used (the edge of the acrylic vessel defines the fiducial volume),there are 0.143 ± 0.0018 IBD Mis-IDed events for every reconstructed IBD event.

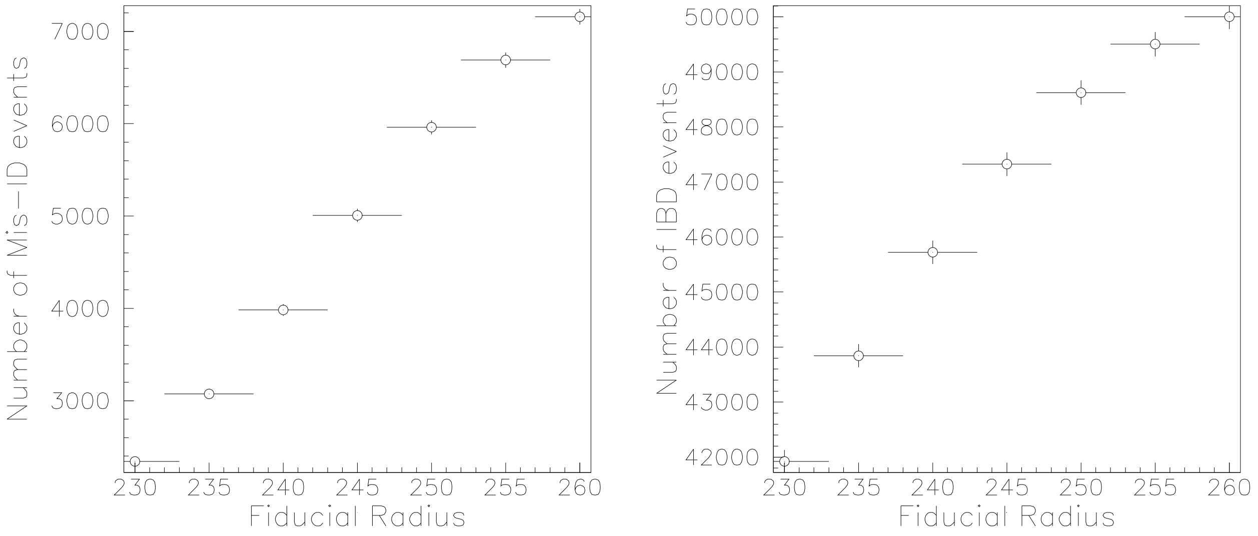
4.2.2 Mis-IDs by Energy

We can also look at the dependence of the rate of Mis IDs on energy. This is important to our study because the ES energy range for Braidwood is 3-5 MeV, not 5-10 MeV, where we are conducting this study. Figures 7 and 8 are the number of Positron Mis-IDs and Neutron Mis-IDs for all energies by visible energy. Figure 9 are the reconstructed IBD events by positron energy for all positron energies. Figure 10 is the ratio of total IBD Mis-IDs (7 plus 8) to the number of reconstructed IBD events. We find from Figure 10 that the number of Mis-IDs to reconstructed IBDs is decreases for lower energies down to 3 MeV, where the ratio begins to rise. At energies above 8 MeV we see a significant increase in the number of Mis-IDs to IBD events. This is most likely because of the lack of reconstructed IBD statistics at high energies. It is the neutron Mis-ID events that increase most drastically with energy, which cast doubts that this increase is due to neutrons that capture quickly after the positron. Thus, we can conclude that our analysis provides an upper bound to the background due to IBD misidentification.

5 Summary

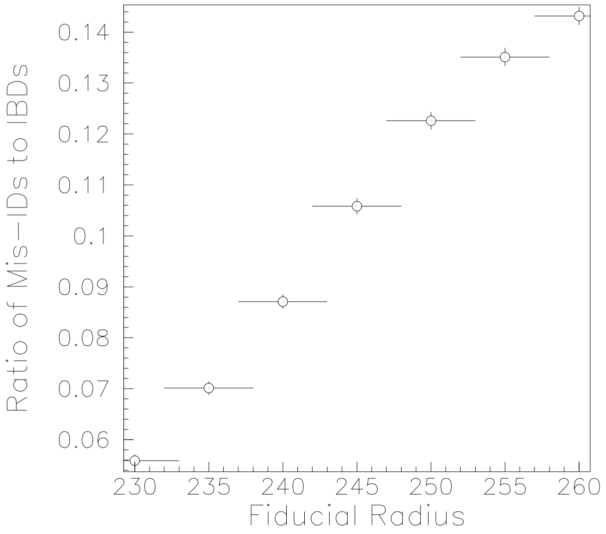
This analysis concludes that by studying IBD Mis-ID rates in the energy range of 5 to 10 MeV, we can compose an estimate to the ES background due to IBD Mis-IDs in the Braidwood ES energy window of 3 to 5 MeV. By comparing the Monte Carlo predicted Mis-ID rate to the reconstructed IBD rate, we can predict the number of Mis-IDs in our data from the number of well reconstructed events. We find that for the 230 cm fiducial volume cut proposed in Braidwood, the rate of mis-IDs to reconstructed IBD events is 0.056 ± 0.0012 for 5 to 10 MeV. Increasing the fiducial volume increases the rate of Mis-IDs, as would be expected. The IBD rate is dependant on energy, especially at low and high energies- we suspect that the large number of Mis-IDs to reconstructed IBDs at high energies is partially due to lack of statistics. There is also an increase in Positron Mis-IDs at high energies due to either high energy positrons with low energy quick capturing neutrons, or low energy positrons with high energy neutron followers. Even at lower energies, Neutron Mis-IDs can be mislabeled by the Monte Carlo as Positron Mis-IDs if the positron energy is not seen.

A factor that may change the ratio of Mis-IDs to IBD events is the 0.5 MeV threshold on ‘seeing’ a neutron follower, which currently allows neutrons between 0.2 and 0.5 MeV to be



(a) Total Mis-IDs vs Fiducial Radius

(b) Reconstructed IBDs vs Fiducial Radius



(c) Ratio of Mis-IDs to IBDs vs Fiducial Radius

Figure 6: (a)Total Mis-IDs vs Fiducial Radius (b)Reconstructed IBDs vs Fiducial Radius (c) Ratio of Mis-IDs to IBDs vs Fiducial Radius. Dimensions for the fiducial radius are in centimeters

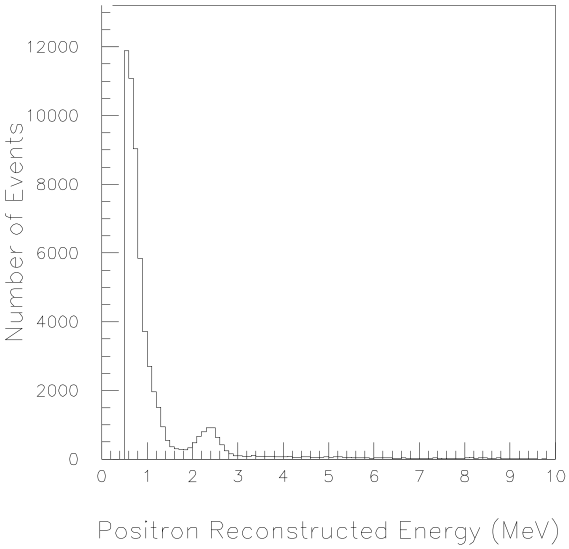


Figure 7: Positron Mis-IDs for all energies. 58923 events

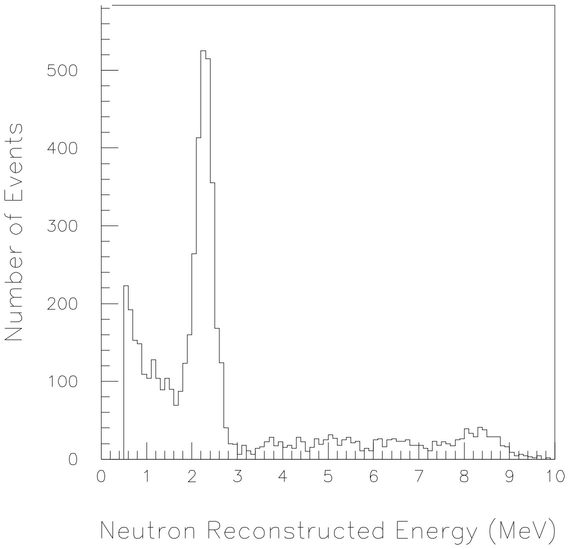


Figure 8: Neutron Mis-IDs for all energies. 7237 events.

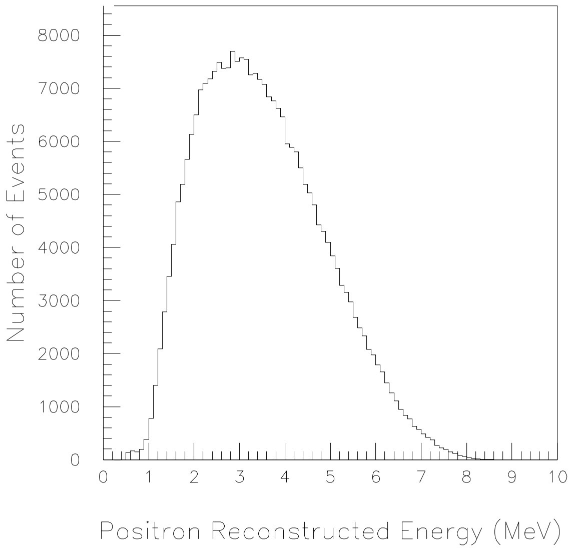
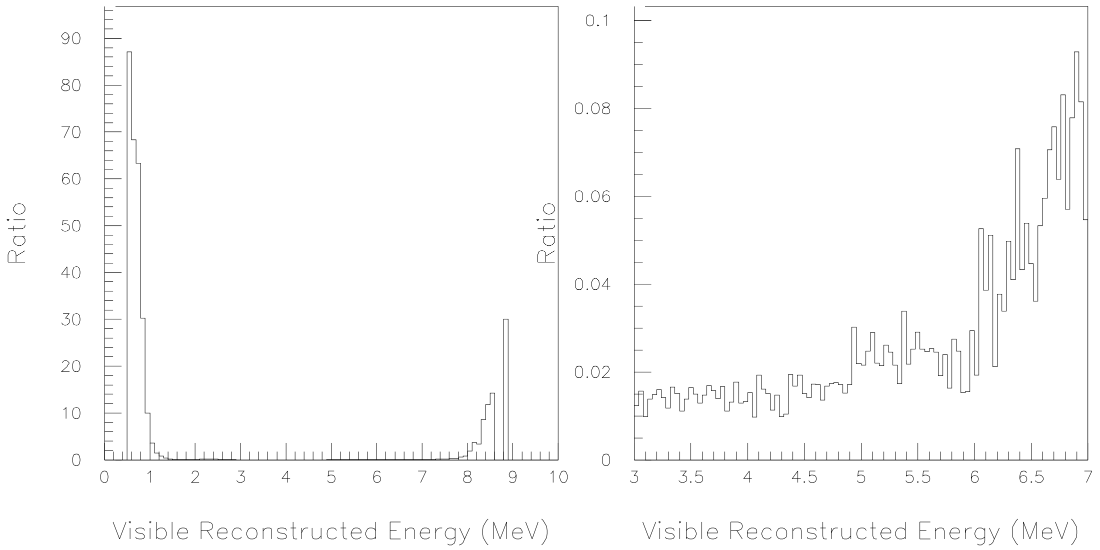


Figure 9: Well reconstructed IBDs by e^+ reconstructed energy. 273416 events.



(a)

(b)

Figure 10: Mis-IDs to Reconstructed IBDs for all energies for (a) all energies (b) 3 to 7 MeV

'unseen', though they are reconstructed by the Monte Carlo.(this we estimate to be within two standard deviations)

6 Next Steps

The obvious next step is to study 'Method 2' proposed in Ref. [1]. This will require a Monte Carlo that simulates ortho positronium, which ReactorFSim currently does not do.

References

[1] “Two ideas for Constraining the IBD Mis-id” J. Conrad

[2] “Positron Annihilation in Liquid Scintillator for Electron Antineutrino Detection,” Y Kino, T Sekine, Y Sato, H Kudo, F Suekane, A-J. Nucl. Radiochem. Sci.- radiochem.org, 2000; http://www.radiochem.org/paper/JN12/j012Kino.pdf