

PMT Charge Response and Reconstruction of Position and Energy for a Reactor θ_{13} Experiment

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1 Introduction

I have taken a first look at the effects of the PMT charge response on position and direction reconstruction for the ‘baseline’ θ_{13} detector. Unlike a water Cerenkov detector, the long time tail on the scintillator’s response is likely to make PMT charge response in a reactor experiment more important than time response. While the question of how well the tubes need to measure charge is a relatively minor one compared to the critical questions of background levels, detector stability and calibration, and number of detector zones, it has the nice feature that it is probably one we can actually answer quickly.

I have used Kansas’s ReactorFsim for the investigation presented here, modified to include a more realistic charge spectrum, based upon the measured response of the SNO PMTs (Hammamatsu R1408). The distribution of ReactorFsim is whatever was current as of January 27, 2004.

2 Charge Spectrum

The charge resolution of a PMT is driven primarily by the gain of the first dynode, because it is here that the electron statistics are lowest. Depending upon the tube, the average gain at the first dynode may be 2 or 3, though some high resolution tubes can be as high as 5. The poisson statistics of these small numbers of secondary electrons leads to a broad

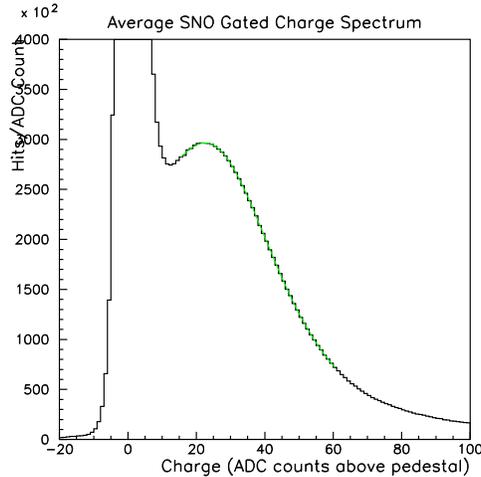


Figure 1: Single pe Distribution for SNO PMTs (Hamamatsu R1408's)

charge response, which is made only broader as the signal propagates through additional stages. Beyond the statistical broadening, interactions within the tube can add to the gain (thus broadening it further). Examples of these interactions are photoelectrons scattering off of the focusing grid or other tube elements; bremsstrahlung photons which produce additional photoelectrons as they reach the photocathode; or ionization of gas within the PMT. Variations in gain from tube-to-tube, if not well calibrated and corrected, will also lead to broadened charge resolution. Lastly, whatever smearing is inherent in the front-end electronics integration (and/or digitization) can broaden things slightly as well.

Figure 1 shows the average single pe spectrum averaged over roughly half of the SNO PMT's, measured in ADC counts above pedestal. The data here were taken in 'gated' mode in which the integrators are gated in-time with light from a laser source placed at the center of the SNO detector. The 'pedestal peak' down at low charge represents all the times in which a photon was not incident upon a photocathode, and so the charge integral is zero. Note in particular the tail on the charge spectrum, which continues out well past the single pe peak, and which is caused by some of the effects mentioned above.

To create a charge response which looks like this charge distribution, I picked a somewhat ad-hoc analytic form, fitted to the spectrum. The analytic form uses a Polya distribution to

represent the single pe shape:

$$P(m) = \frac{m(mQ)^{m-1}}{\Gamma(m)} e^{-mQ} \quad (1)$$

where Q is measured in units of photoelectrons. I also added an exponential to represent the high charge tail, and to ‘turn off’ the exponential term near pedestal, I include a factor which is just an exponential rise (an ‘RC’ curve). The fit to this analytic form is superimposed on the charge histogram of Figure 1, fitted from about the single pe peak (at around 25 counts above pedestal) to 60 counts above pedestal. The χ^2 for the fit is not particularly good, but for the purposes here the spectrum looks realistic enough. Unfortunately, it is very hard to fit the spectrum below the single pe peak, because the pedestal peak interferes quite a bit. Discriminated (rather than gated) data could be used instead, but then the resulting spectrum is discriminator-threshold dependent. For a full hit-level Monte Carlo, we ultimately will want to include the discriminator threshold efficiencies, and so I have tried to start with the full single pe spectrum here.

To include this charge distribution in ReactorFsim, I added a method to the ReactorDetector class called GetQ, which takes as input the number of photoelectrons created on a given tube, and returns the measured charge in units of equivalent pe. For n_{pe} photoelectrons, the charge spectrum is sampled n_{pe} times and the charges added and convolved with a gaussian to represent the smearing of the front end electronics. Figure 2 shows the charge distribution generated by GetQ for a single photoelectron (the cutoff at about 6 pe is artificial and was removed for the rest of the study). Figure 3 shows the charge spectra for single and multiple photoelectrons, compared to the generated number of pe.

3 Position Reconstruction

ReactorFsim includes a simple position reconstruction algorithm, essentially a fitter ‘in closed form’ which calculates the dipole moment of the charge distribution, and a second stage which provides some improvement on the initial fit. For the baseline detector, position reconstruction is likely to be used only through a Δr cut between the positron and neutron positions in order to remove accidental backgrounds, and therefore may not be too critical. Nevertheless, we would expect that a smearing of the charge resolution will have a noticeable

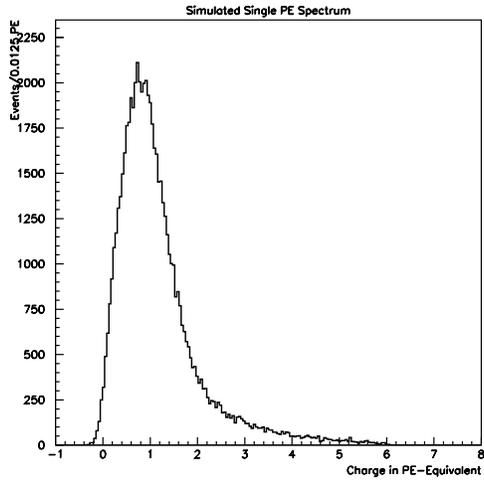


Figure 2: Simulated single pe charge spectrum

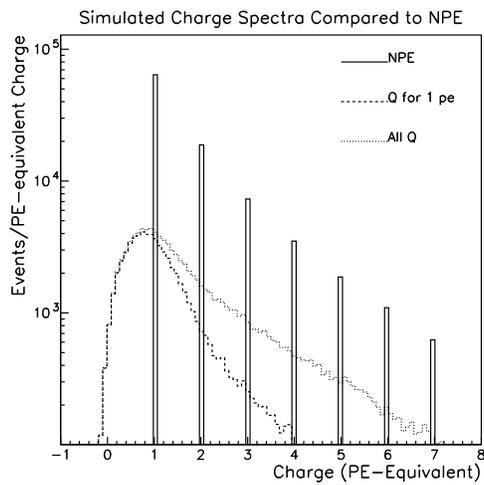


Figure 3: Number of photoelectrons compared to charge spectra

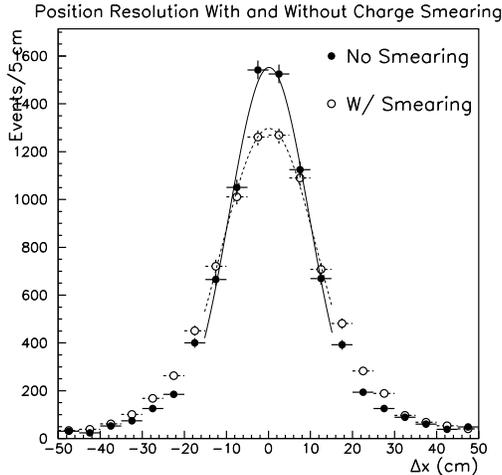


Figure 4: Position resolution in the x dimension, with and without the smearing due to realistic PMT charge response

effect on a position reconstruction algorithm based on charge alone.

Figure 4 shows the position resolution in the x coordinate for positrons, with and without the PMT charge smearing. We see that the resolution is broadened a bit (roughly 2 cm, from 9.5 cm to 11.5 cm) from the PMT charge response, which is not too bad. To see the effects on a potential Δr cut, I plot in Figure 5 the difference in position of the positron and neutron in an event, with and without the effects of charge smearing. We see that the distribution shifts slightly, by roughly 5 cm. To know how big an effect this is on background rejection, we'd need to know the distribution of accidentals in Δr , which will depend on their source—accidentals from γ -rays making it to the scintillator will be peaked at high Δr (and therefore this is a very small effect), while radioactivity inside the scintillator will be flat. However, at first look, this does not seem too bad of an effect.

One additional variable worth considering here is photocathode coverage. The charge smearing means that two PMT hits are worth more than 2 pe in one PMT—you know if there are two PMT's hit, that you have at least 2 pe, whereas with just one tube you do not. Figure 6 shows the same Δr distribution as shown in Figure 5, but for a detector with a 10% photocathode coverage (as compared to the 20% used earlier). We see that in the lower coverage detector the difference between the reconstruction of events with perfect and smeared charges is larger, but not too bad: the shift in the reconstruction of Δr is perhaps

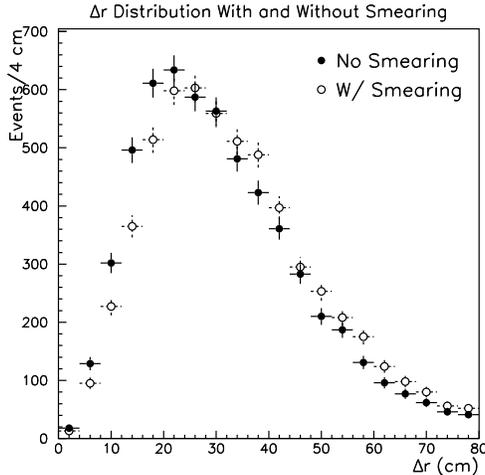


Figure 5: Distribution of reconstructed distance between positron and neutron, with and without the smearing due to realistic PMT charge response

gone from 5 cm to 8 or 9 cm.

4 Energy Reconstruction

ReactorFsim also includes an algorithm to reconstruct the event energies, which uses the input photocathode coverage, quantum efficiencies, and the energy scale itself (number of photons per MeV). The reconstructed energy is therefore proportional to the observed number of photoelectrons, and we expect that the smearing out of the charge measurements by real tubes will have a noticeable effect on the reconstructed energy spectrum.

Figure 7 shows a comparison between the reconstructed energy spectrum for the default ReactorFsim simulation (no PMT charge smearing) and the same spectrum with the charge smearing described in Section `refsec:qspec`. What we see is that—not surprisingly—the energy spectrum with the smeared charges is about 25% broader than that without. The apparent shift in the mean is just a consequence of the fact that the energy scale (the number of photons per MeV) has not been change to ‘equivalent pe per MeV’ which is a smaller number due to the charge smearing.

To see if a low photocathode coverage detector is affected more than a high photocathode coverage detector, I looked at both a 10% coverage detector and a 1% coverage. The 10%

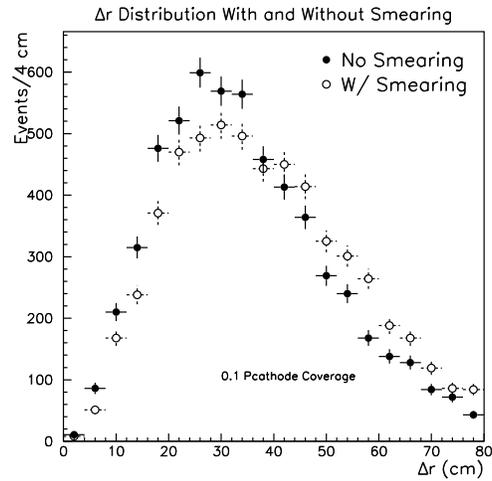


Figure 6: Distribution of reconstructed distance between the positron and neutron for a 10% coverage detector.

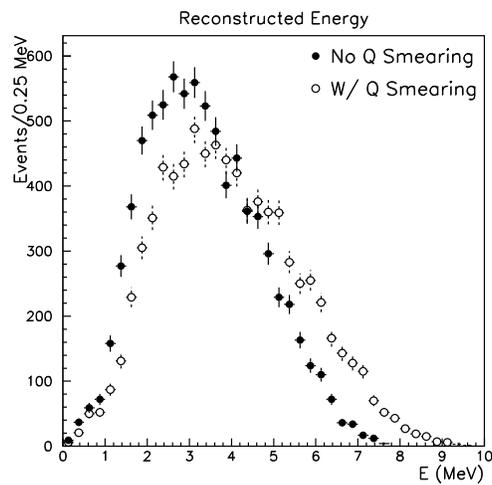


Figure 7: Reconstructed energy spectrum with and without charge smearing.

detector looked no different, which is somewhat surprising. This may be a consequence of the parameterized way ReactorFsim handles hits, but I would have to look at this some more.

5 Conclusions

The conclusion to all this is not at all surprising: ‘better charge resolution is better’. However, I still think we need to look at this a bit more with a hit-level Monte Carlo like the recent Geant4 studies being done at Kansas, since I would like to have a better idea of how the distribution of PMT hits (as opposed to PMT charge) affects things.