Simulation for the Braidwood Neutrino Experiment

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1 Introduction

ReactorFsim is the simulation package for the Braidwood Neutrino Experiment. The purpose of ReactorFsim is to provide a basic simulation tool which can rapidly produce a large number of events on a desktop-sized computer. Because we use parametrized information where possible, ReactorFsim can simulate events more quickly than other applicable Monte Carlo programs such as Geant4 [1] or MCNP [2]. For ease and portability the Monte Carlo uses the random number generators included in the standard CERN program libraries [3]. The code is currently running on both Linux and Solaris platforms.

2 Event Generator

ReactorFsim contains a parametric Monte Carlo event generator that can create several types of events, including inverse β-decay (IBD) interactions,

$$\bar{\nu}_e + p \to e^+ + n, \tag{1}$$

and elastic scatters,

$$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-, \tag{2}$$

of anti-electron neutrinos generated by a nuclear reactor source. Other classes of events which can be generated by the Monte Carlo are fission decays of 252 Californium source(s) and high-energy gamma radiation from U/Th isotopes in the photomultiplier tube (PMT) glass. Additionally, the event generator can accept as input particle information produced by the separate Braidwood Geant4 veto simulation detailed in the attached document, "Design of Veto System," allowing for combined veto and detector background studies.

This summary focuses on the inverse β-decay event generation. The reactor $\bar{\nu}_e$ flux is parametrized from the calculation by Bemporad, Gratta, and Vogel [4]. The $\bar{\nu}_e$ cross section and e^+ and n angular distributions are given by the $O(1/M)$ calculation by Vogel and Beacom, where M is the nucleon mass [5]. Figure 1(a) shows the generated $\bar{\nu}_e$ energy spectrum.

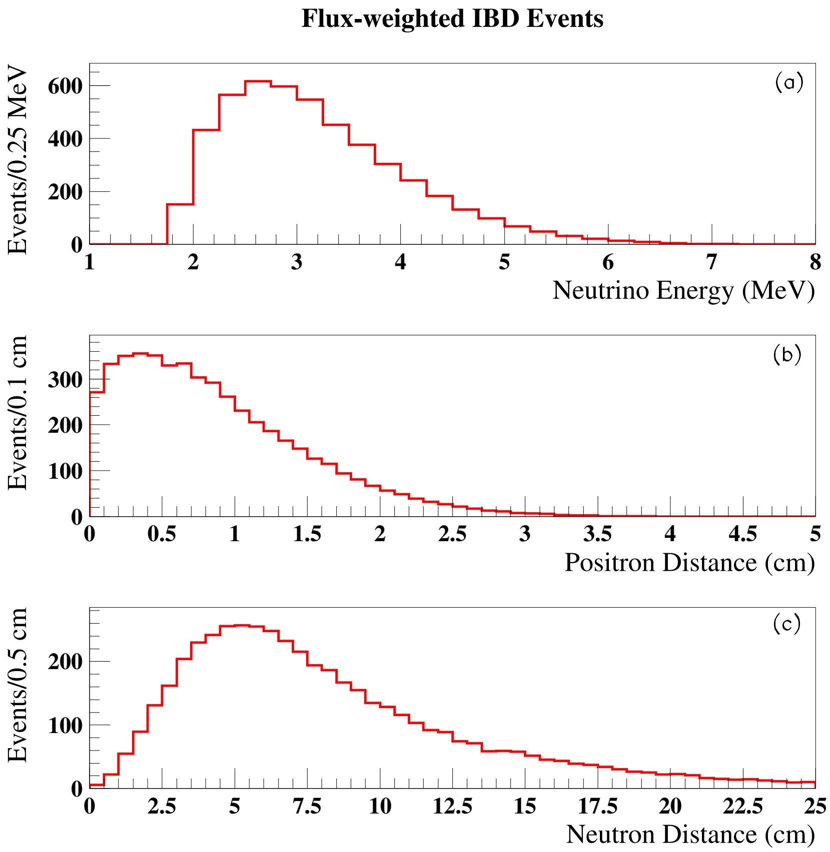

Figure 1: Flux-weighted IBD events: (a) generated $\bar{\nu}_e$ energy in MeV, (b) e^+ range from IBD vertex to annihilation in cm, (c) n range from IBD vertex to capture in cm.

Medium	τ (cm)
Gd-loaded scintillator	1000
acrylic	50
mineral oil	1000

Table 1: Attenuation lengths of all media in cm.

3 Detector Simulation

ReactorFsim also contains a spherical detector simulation through which the particles generated in the event are propagated. The default detector consists of a 1 cm thick inner acrylic vessel of radius 260 cm containing Gadolinium (Gd) doped liquid scintillator surrounded by a 90 cm thick mineral oil buffer. 935 8-inch PMTs are placed uniformly inside the oil buffer for ∼25% photocathode coverage. An optional third zone of liquid scintillator contained between the inner vessel and oil buffer in a second acrylic vessel may be added.

3.1 Secondary Particles

The IBD e^+ propagation is modeled via the Berger-Seltzer formula for dE/dx [6] until it annihilates, producing a pair of 0.511 MeV/c^2 gamma-rays. Figure 1(b) shows the simulated e^+ range from IBD vertex to annihilation. The IBD n range is modeled by a series of elastic scatters until it is captured on a nucleus. The cross sections for elastic scatter and capture are taken from the nuclear reaction database ENDF/B-VI compiled by Brookhaven National Laboratory [7]. Figure 1(c) shows the simulated n range from IBD vertex to capture.

The number of gammas released by the n capture on Gd is modeled by a Poisson fluctuation around 3; capture on Hydrogen and Carbon are each modeled with 1 gamma. All capture gammas are released isotropically. The Compton scattering of the n capture and e^+ annihilation gammas is described by the Klein-Nishina formula down to an 0.1 MeV/c^2 cutoff.

The time, position, and magnitude of the energy depositions from the e^+ and the scattering of its annihilation gammas are recorded as "positron-like" energy. The same information for the n elastic scatters and the scattering of its capture gamma(s) is recorded as "neutron-like" energy.

3.2 Detector Response

All energy depositions in the scintillator are converted to optical light assuming a Gaussian distribution centered around 5300 photons/MeV. The light is tracked through all applicable media (scintillator, acrylic, or oil) along a straight path from the position of the energy deposit (r_E) to the position of each PMT (r_{PMT}). Thus, the solid angle of the light visible

Effect	Description
γ/MeV	Gaussian distribution centered at 5300
solid angle	$\Omega = r_{PMT}^2/r_E^2$
attenuation	$A(dx) = e^{-\frac{dx}{\tau}}$, applied in all media
Cerenkov photons	generated in all media
	added to any optical photons
PMT coverage (PMT^f)	25%
PMT diameter	20.16 cm
PMT quantum efficiency (PMT^{QE})	0.2

Table 2: Physical effects and PMT and scintillator properties used to obtain the number of optical photons seen by each PMT.

to each PMT is

$$\Omega(r) = r_{PMT}^2/r_E^2. \tag{3}$$

The attenuation in all media is modeled by

$$A(dx) = e^{-\frac{dx}{\tau}}, \tag{4}$$

with the attenuation length (τ) for each medium given in Table 1. Cerenkov photons are simulated in all media for electrons above threshold, and the Cerenkov light is summed with any scintillation light, increasing the energy in the e^+-like spectrum by $\sim$5% for energies above $\sim$4 MeV. The number of photoelectrons in each PMT is then modeled by a Poisson fluctuation around the total number of photons arriving at the tube, as summarized in Table 2. From the number of photoelectrons we model the charge (Q) in a given PMT from each energy deposit with a spectrum based on the Hamamatsu R1408 tubes.

4 Simple Reconstruction

From the simulated PMT charges, we perform a simple first pass at energy reconstruction. For the i^{th} PMT we sum over all energy depositions (N_E) to get the total charge for that tube, Q_i. We then sum over all tubes to get the total reconstructed energy observed in the detector:

$$E = \sum_{i}^{N_{PMT}} \sum_{n}^{N_E} \frac{1}{PMT_i^{QE} \times PMT^f \times (\gamma/MeV)^n} \frac{Q_i^n(A_i^n, \Omega_i^n)}{A_i^n \times \Omega_i^n}, \tag{5}$$

where A_i^n and Ω_i^n depend on the relative positions of PMT i and energy deposit n. Much improvement has already been made to the event reconstruction, including a full energy reconstruction based on reconstructed positions, but is not reported here.

Figure 2 shows the simulated spectra for e^+-like and n-like reconstructed energies for events generated with an IBD vertex out to the steel vessel (vertex radius $R < 350$ cm).

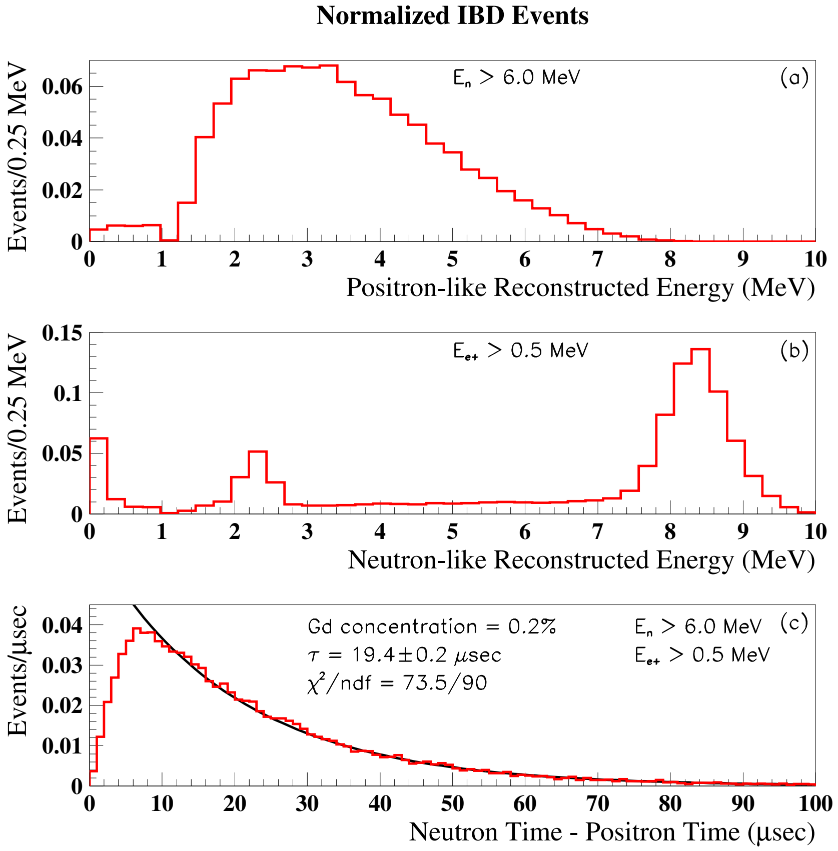

Figure 2: Normalized IBD events with vertex $R < 350$ cm: (a) simulated e^+-like energy in MeV with $E_n > 6.0$ MeV, (b) simulated n-like energy in MeV with $E_{e+} > 0.5$ MeV, (c) the time from e^+ annihilation to n capture in μsec with $E_{e+} > 0.5$ MeV and $E_n > 6.0$ MeV including a fit to an exponential decay. The fit yields a characteristic n capture time (τ) of 19.4±0.2 μsec for a Gd concentration of 0.2%.

Positron and neutron minimum energy cuts have been applied as given in the figure: $E_{e+} >$ 0.5 MeV and $E_n > 6.0$ MeV. The low energy (< 1 MeV) tail in the e^+-like energy distribution arises primarily from events generated near the acrylic vessel in the oil buffer where the neutron propagates into the scintillator and is captured on Gd and a small number of photons from the positron are generated by Compton-scattered gammas trailing back into the scintillating region and Cerenking particles in the oil.

ReactorFsim also saves particle timing information for the IBD event. Time zero is defined to be the IBD interaction. Time is calculated for all secondary particle propagation, including γ Compton scattering. Figure 2(c) shows the time from e^+ annihilation to n capture in μsec with both energy cuts applied ($E_{e+} > 0.5$ MeV and $E_n > 6.0$ MeV) with a fit to an exponential decay. The fit yields a characteristic n capture time (τ) of 19.4±0.2

μsec for a Gd concentration of 0.2%, which agrees well with expectation.

5 Conclusion

ReactorFsim is currently the primary simulation tool for the Braidwood detector. It has been used to study several important systematic effects, in particular using a fit to the energy peak from n capture on Gd (with a mean of $\sim$8 MeV) to measure the relative energy scale of different detectors, as presented in Section 2.2 of the Braidwood Project Description, which this document supplements. This technique will be an important handle to reduce the relative energy scale systematic between the near and far Braidwood detectors without requiring an outer "γ-catching" unGd-doped scintillating region.

ReactorFsim is still under rapid development and will likely remain the main simulation tool for the Braidwood detector in the near future. The long-term goal will be to develop a full Geant4 detector simulation combined with the Braidwood veto simulation already under development.

References

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