Fast Simulation for the Braidwood Neutrino Experiment

Matthew Worcester
(for the Braidwood Collaboration)
University of Chicago

(Dated: May 18, 2005)

We provide a brief description of ReactorFsim, the Braidwood Neutrino Experiment fast simulation software. ReactorFsim contains a parametric Monte Carlo event generator for inverse β-decay interactions of the reactor $\bar{\nu}_e$ and a hit-level simulation of the Braidwood detector. It includes a simple energy reconstruction of the event from the simulated detector output.

Contents

I. INTRODUCTION

The purpose of ReactorFsim is to provide a simple simulation package 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 much more quickly than other applicable Monte Carlos such as GEANT4 or MCNP. For ease and portability the Monte Carlo uses the random number generators included in the standard CERN program libraries [1]. The code is currently running on both Linux and Solaris platforms.

II. EVENT GENERATOR

ReactorFsim is the fast simulation package for the Braidwood Neutrino Experiment. It 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), high-energy gamma radiation from U/Th isotopes in the photomultiplier tube (PMT) glass, and cosmic-ray muons.

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 [2]. 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 [3]. Figure 1(a) shows the generated $\bar{\nu}_e$ energy spectrum.

III. 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

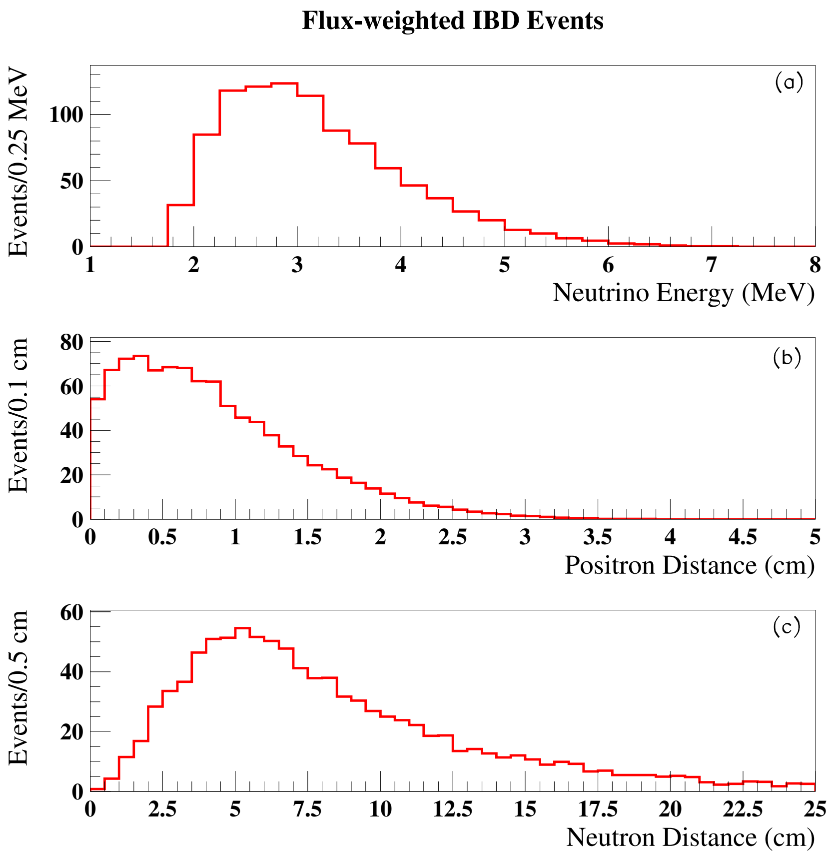

FIG. 1: Flux-weighted IBD events: (a) generated $\bar{\nu}_e$ energy in MeV, (b) e^+ range from IBD vertex to annihilation in cm, (c) n range from IBD vertex to capture in cm.

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.

A. Secondary Particles

The IBD e^+ propagation is modeled via the Berger-Seltzer formula for dE/dx [4] 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

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

TABLE I: Attenuation lengths of all media in cm.

are taken from the nuclear reaction database ENDF/B-VI compiled by Brookhaven National Laboratory [5]. 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.

B. 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 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 I. 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

Effect	Description
γ/MeV	Gaussian distribution centered at 5300
solid angle	$\Omega = r^2_{PMT}/r^2_E$
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 II: Physical effects and PMT and scintillator properties used to obtain the number of optical photons seen by each PMT.

above ~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 II. 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.

IV. 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:

$$Q = \frac{1}{PMT_{QE} \times PMT_F \times \gamma/MeV} \sum_i^{N_{PMT}} \sum_n^{N_E} \frac{Q_i^n(A_i^n, \Omega_i^n)}{A_i^n \times \Omega_i^n}, \tag{5}$$

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 positron-like and neutron-like energies seen by the detector.

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

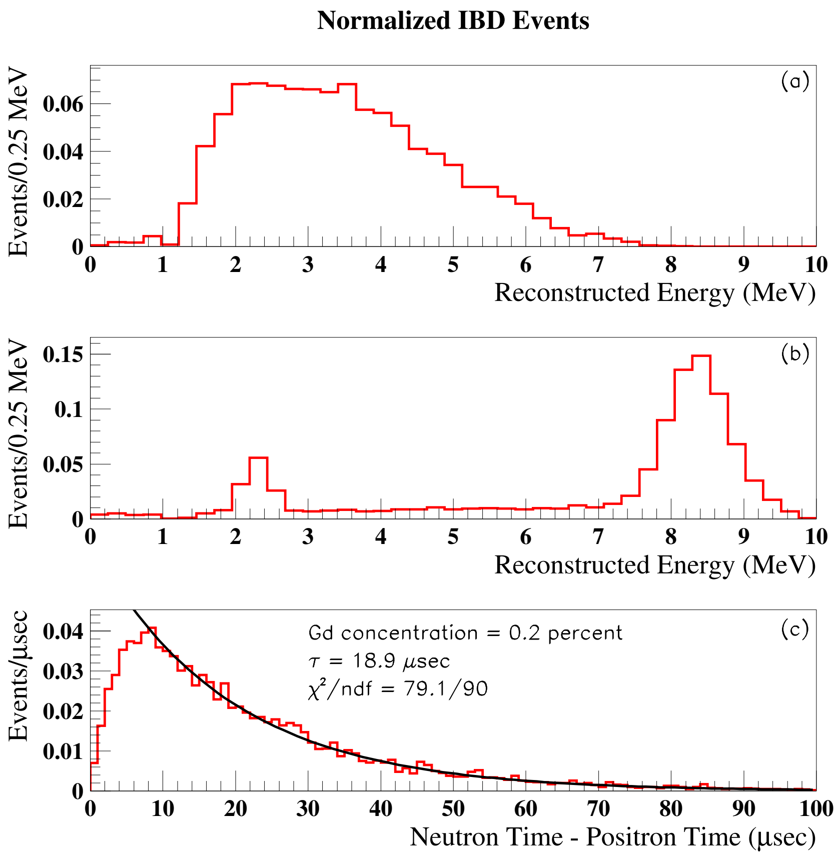

FIG. 2: Normalized IBD events: (a) simulated e^+-like energy in MeV, (b) simulated n-like energy in MeV, (c) the time from e^+ annihilation to n capture in μsec with a fit to a exponential decay. The fit yields a characteristic n capture time (τ) of 18.9 μsec for a Gd concentration of 0.2%.

capture in μsec with a fit to a exponential decay. The fit yields a characteristic n capture time (τ) of 18.9 μsec for a Gd concentration of 0.2%, which agrees well with expectation.

V. 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 primary simulation tool for the Braidwood detector in the near future.

[1] CERN Program Library, URL `http://wwwasd.web.cern.ch/wwwasd/cernlib/`.

[2] C. Bemporad, G. Gratta, and P. Vogel, Rev. Mod. Phys. **74**, 297 (2002).

[3] P. Vogel and J. F. Beacom, Phys. Rev. **D60**, 053003 (1999).

[4] Berger and Seltzer, Nucl. Instrum. Meth. **104**, 317 (1972).

[5] Evaluated Nuclear Data File (ENDF), URL `http://www.nndc.bnl.gov/exfor/endf00.htm`.