Improvements on Monte Carlo Simulation and Studies of Absolute Detection Efficiency at Daya Bay

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Abstract

The Daya Bay experiment has made the most precise measurement of neutrino mixing angle θ_{13} and the first direct measurement of the $\overline{\nu}_e$ mass-squared difference Δm^2_{ee} through the relative measurements between near and far detectors. In addition, efforts are made toward the absolute reactor flux and spectra measurements, which require a precise understanding of the absolute detection efficiency and detector energy response. The Monte Carlo simulation plays a crucial role in understanding the detector performance. A Geant4-based full detector simulation software has been built under the Gaudi framework, and is tuned with various data sets. This poster will describe details of the improvements on Monte Carlo simulation and studies of the absolute detection efficiency at Daya Bay.

Introduction

Daya Bay simulation software has been developed based on GiGa/Geant4 within the offline software framework known as NuWa, in which the detailed detector geometries have been constructed. Kinds of generators have also been custom built, like IBD, cosmic muons and specific decay chains. Optical photons generated in liquid scintillation (LS) will be tracked by Geant4 for precision simulations. The electronics and trigger simulations are implemented to model the response of electronics and trigger systems.

We made many efforts to improve Monte Carlo (MC) simulations to match the observed detector response. The main improvements include:

1. Get MC inputs from real data
2. Study time components of LS
3. Improve thermal neutron scattering simulation
4. Investigate several gamma spectrums from nGd capture

Finally, based on tuned MC, we will show some studies on absolute detection efficiency, which are essential inputs of absolute reactor flux and spectra measurements.

MC Inputs from real data

- Optical properties

Most of optical properties of materials used in central detector (AD) have been well measured, like attenuation length, emission spectrum, refractive index, reflectivity, etc. These parameters can be used in MC directly. For other optical properties with large uncertainties, we can tune them to find the best values that can well match data.

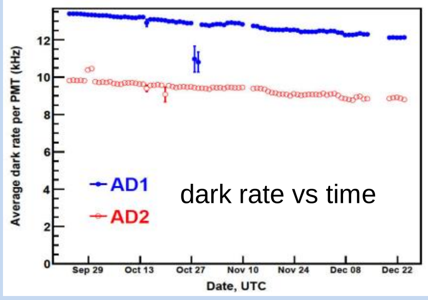
- Properties of PMTs

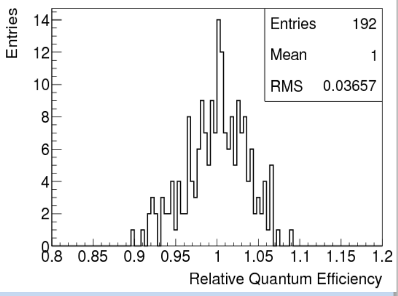
The gain, dark rate and quantum efficiency of each PMT are key MC inputs and can be gotten from different datasets.

a) gain (ADC/single photon-electron) is calibrated by fitting the single p.e. peak.

b) dark rate is measured by random trigger data. Dark rate versus time is shown in left figure below.

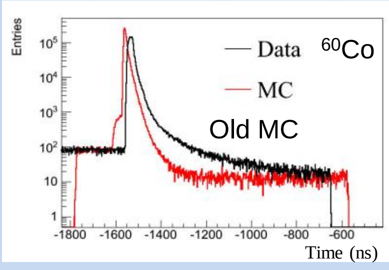
c) Relative quantum efficiency (RQE) is measured by low energy calibration source (^{68}Ge) in ACU-A. RQE is shown in right figure .

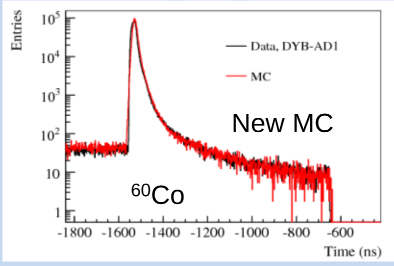




Time components of liquid scintillator

- Large discrepancy exists between old MC and Co60 data for PMT hit time (left figure).
- The long tail feature does not appear in LED data.
- So, besides the known fast and "slow"(marked as "medium" in table) time components in LS, we added a slower component and tuned MC to match with data.
- We did similar adjustments for proton and alpha.
- Measure time components using a standalone experiment (γ source), result shown in right figure.





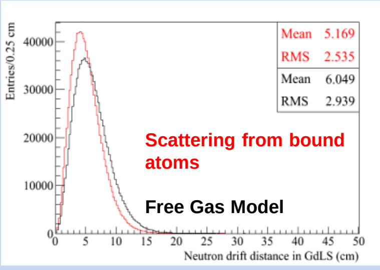
- Three time components and fractions are summarized.

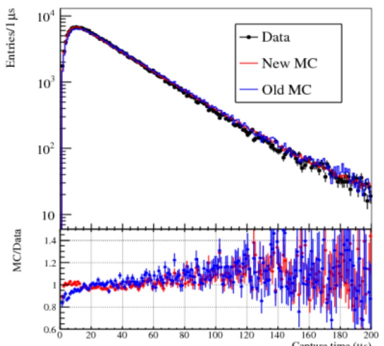
	Fast (ns)	Medium (ns)	Slow (ns)	Fast Ratio	Slow Ratio
γ (tuned)	1	26	200	70%	4.5%
proton	1	34	220	65%	22.1%
α	1	35	220	65%	22.8%
γ (meas.)	6.9	30	148	80.5%	6.7%

Thermal neutron scattering (TNS)

Thermal neutron scattering can affect the spill-in ratio, which is a key parameter in absolute efficiency studies.

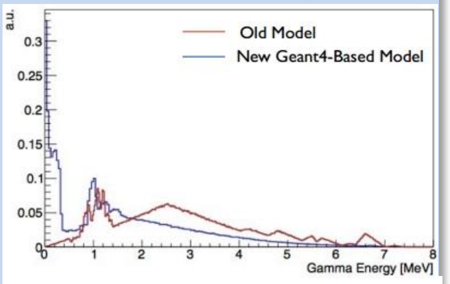
- "Free gas model" can not well simulate thermal neutron scattering process, we need to consider chemical bond effect.
- Due to no cross section data of TNS available in Geant4 for scintillator, we use C from graphite and H from water.
- After updates, the new MC (red color in right two plots) has better agreements with data.
- Based on truth information, we also compared neutron drift distance in GdLS for two models, shown in left figure.

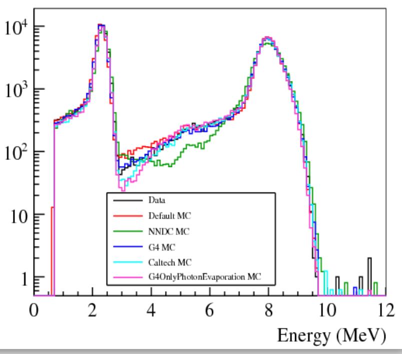




Gamma spectrum from nGd capture

- The gammas released from nGd capture provide the delayed signals of IBD reactions.
- Using Daya Bay data, we investigated several gamma spectra of nGd capture from different sources, shown in lower plot.
- Finally, we found the spectrum based on Geant4 provides the best fit to data, and a spectrum from HPGe measurements at Caltech is also acceptable.
- The upper plot shows the old gamma spectrum (used as default before) and new G4-based gamma spectrum.



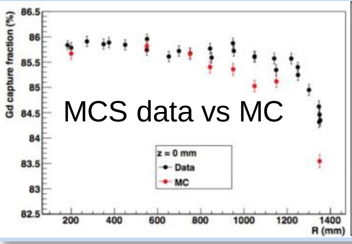


Absolute detection efficiency

- The error on absolute flux measurement is dominated by absolute efficiency uncertainty.
- The main sources of efficiency uncertainty are from Gd capture ratio, delayed energy cut and spill-in.

Gd capture fraction (F_{Gd})

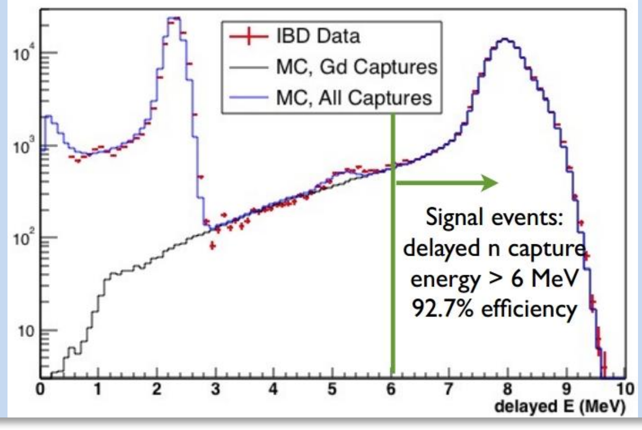
- Using new MC to estimate the expected Gd capture fraction for IBDs, which is determined by Gd concentration and leakage of neutrons out of GdLS.
- Gd capture fraction at detector center measured in many datasets and compared to MC, shown in table below.
- Full-volume Gd fraction measured by manual calibration system (MCS) using a PuC source.
- The relative uncertainty is estimated to be 0.95%.



Data Set	$E_{rec,p}$ (MeV)	KE_n (MeV)	E_γ (MeV)	F_{Gd}	Unc_{stat}
Spallation n	-	range	range	85.7	0.2
AmC	0-4	3-5.5	-	85.4	0.15
AmBe	0-7	4-10	-	85.4	0.1
PuC, Ground State	0-4	3-7.5	-	85.5	<0.01
PuC, 1st Excited	0.5-1	<0.6	-		
PuC, 2nd Excited	5.5-7	<0.6	6.13	85.5	<0.1
IBD MC	0.7-12	<0.1	-	85.7	<0.1

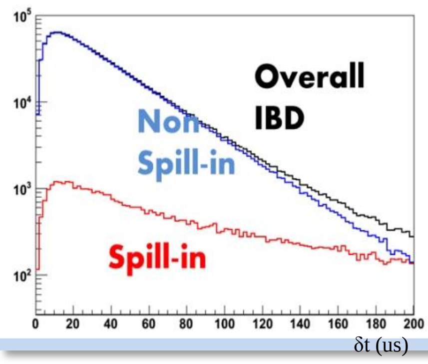
Delayed energy cut

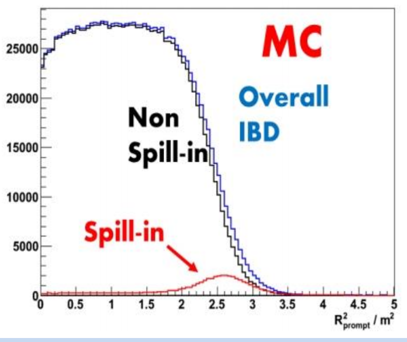
- The new MC can well match with data at the region > 3MeV, shown as blue line in figure.
- Since the nH peak obscures the nGd tail, to be conservative, we assign 100% uncertainty for the region < 3MeV.
- The gamma spectrum from Caltech HPGe measurement is applied to do cross check and consistent within the errors.
- The relative uncertainty is estimated to be 0.97%.



Spill-in

- Spill-in occurs when an IBD neutron produced outside the target drifts into target and forms an IBD candidate.
- The spill-in ratio of IBDs is predicted by MC.
- AmC source in LS is used to validate MC, shows MC and data agree within 1% for high energy neutron.
- The features of IBD coincidence time (left figure) and positions (right figure) are different for normal and spill-in IBD candidates, which can be used to constrain the uncertainty of spill-in ratio.
- Combine all studies, the relative uncertainty is conservatively estimated to be 1.5%.





Other contributions

- The prompt energy, timing and flasher cuts have quite high efficiency, which means small errors.
- Muon veto and multiplicity cut efficiencies can be calculated precisely.
- Target protons uncertainty from target mass, proton density measurements.

Summary of absolute efficiency

Input	ϵ	$\delta\epsilon$	$\delta\epsilon/\epsilon$
Target protons	-	-	0.47%
Flasher cut	99.98%	0.01%	0.01%
Muon veto cut	-	-	0.02%
Multiplicity cut	-	-	0.02%
Capture time cut	98.70%	0.12%	0.12%
Prompt energy cut	99.81%	0.10%	0.10%
Gd capture ratio	84.2%	0.8%	0.95%
nGd detection efficiency	92.7%	0.9%	0.97%
Spill-in correction	104.9%	-	1.50%
Combined	80.6%	-	2.08%

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