On the Efficiency Requirement for the Muon System

Kirk T. McDonald

Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544

(October 5, 2006, updated Jan. 13, 2007)

Abstract

The main need for high efficiency in the muon system is to suppress "fast neutron" backgrounds in the antineutrino detectors. Present estimates of the rate of this background rate suggest that it suffices for the muon system to have 95% efficiency (at 95% confidence level). A muon system based on a 2.5-m-thick water pool has an intrinsic inefficiency of 1.5% due to muons that do not pass through the pool. Then, if the efficiency of detection of muons that enter the system is 99%, we need to know this efficiency to 1.5% to meet the requirement that we know the overall system efficiency to be $> 95\%$ at 95% confidence. The overall efficiency can be measured to 1% accuracy using a trigger on "fast neutrons" in the antineutrino detectors whose energy deposition is 10-20 MeV rather than 1-10 MeV. This scenario permits considerable simplification of the muon system, to one based on a single technology.

1 What Efficiency Do We Need and How Well Do We Need to Know It?

The muon system for the Daya Bay Reactor Antineutrino Experiment [1] serves to tag cosmic ray muons so that offline analysis cuts can be made to minimize backgrounds from neutrons and from β-neutron emitters such as ^{9}Li that are produced in nuclear interactions of the muons. High efficiency of the muon system is desired because the rate of (single) neutrons observed in the antineutrino detectors for cosmic-ray muons is roughly 10-15 times that due the antineutrino interactions,[1] while we would like the neutron-related background to be no more than 0.1% of the antineutrino signal. That is, we desire a suppression of neutron-related backgrounds by a factor of 10^4 with respect to the rate of cosmic-ray-induced neutrons.

The antineutrino signal is a double coincidence of a "prompt" energy deposition of 1-8 MeV by the positron in the inverse β-decay reaction,

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

on free proton in the Gd-loaded liquid scintillator of the antineutrino detectors, and a "delayed" energy deposition of ≈ 8 MeV from the cascade of γ's following capture of the (thermalized) neutron on a Gd nucleus. The time constant for the delayed-neutron capture is about 30 μs.

[1]J. Cao, Oct. 3, 2006: "Using Yifang's empirical formula [2] and the muon flux/mean energy quoted in CDR [1], the neutron yield in 20-ton Gd-LS per day is 16000 at the DYB near site, 10800 at the LA near site, and 1120 at the Far site." The antineutrino interaction rates per 20-ton detector are 930/day in the Daya Bay near site, 730/day at the Ling Ao near site, and 90/day at the Far site according to Table 3.8 of the CDR.

The cosmic-ray-neutron background is due to a double coincidence of a "fast" neutron interaction in the liquid scintillator that results in a recoil proton of energy 1-8 MeV, and an $\approx$ 8-MeV signal from the delayed capture of that neutron on a Gd nucleus.

The rate of neutrons that mimic the inverse β-decay signal is estimated to be about 2% of the rate of inverse β-decay. For example, the expected rate of antineutrino interactions in a 20-ton module at the Far site is 90/day according to Table 3.8 of [1], while the expected rate of background from neutrons is 2/day according to Table 3.5 of [1], which is reproduced as Table 1 below). A factor of 20 reduction in this background via tagging by the muon system will reduce its rate to the desired level of 0.1% of the inverse β-decay rate. To accomplish this, the muon system must be 95% efficient at tagging the muons that create the background neutrons.

Rate/day/module		DYB site	LA site	Far site
$\overline{\nu}_e$ signal		930	730	90
All neutrons		16,000	10,800	1120
Fast neutron	tagged	19.6	13.1	2.0
	untagged	0.5	0.35	0.03
Single neutron	tagged	476	320	45
	untagged	8.5	5.7	0.63

Table 1: Neutron rates in a 20-ton module at the Daya Bay sites. The rows labeled "tagged" refer to the case where the parent muon track traversed the veto detectors, and thus it could be tagged. Rows labeled "untagged" refer to the case where the muon track was not identified by the muon detectors, *i.e.*, where the muon did not pass through the muon detectors.

There are two classes of inefficiencies. First, the observed neutrons could be produced by muons that do not pass through the muon system. Second, the neutrons could be due to muons that do pass through the muon system but are not detected by it. Our present estimate is that a muon system based on an active water pool that extends 2.5 m beyond the antineutrino detectors in all directions could tag 98.5% of all neutron-induced background, assuming 100% efficiency for the muon system. For example, the rate of "untagged" muons that produce "fast" neutron backgrounds in a 20-ton detector at the Far site is 0.3/day, compare to a rate of 2/day for "tagged" muons, according to Table 1. That is, only 1.5% of all neutron-background events are due to muons that completely miss a water pool of 2.5 m thickness.

Increasing the thickness of the water pool from 2.5 m to 3 m would reduce the rate of neutron-background events that miss the pool to about 1%, according to Fig. 5.12 of [3], which is reproduced as Fig. 1.

To maintain a total efficiency of 95% for tagging the neutron background events, the

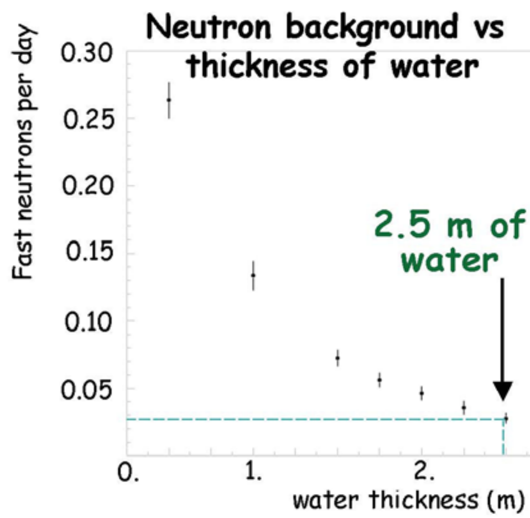

Figure 1: Number of fast neutrons per day for a 20-t module at the far site of Daya Bay as a function of the thickness of water buffer. From [3].

muon system must be 96.5% efficient in detecting muons that enter a 2.5-m thick water pool surrounding the antineutrino detectors.

This specification of 96.5% detection efficiency for the muon system should be interpreted to mean that the muon-detection efficiency is 96.5% or greater with, say, 95% confidence. That is,

$$\epsilon - 2\sigma_\epsilon > 0.965, \tag{2}$$

where ϵ is the detection efficiency for muons that pass through the muon system, and σ_ϵ is the uncertainty on efficiency ϵ. For example, this specification can be met by the requirements that $\epsilon = 0.97,\ \sigma_\epsilon = 0.0025$, or by $\epsilon = 0.98,\ \sigma_\epsilon = 0.0075$, or by $\epsilon = 0.99,\ \sigma_\epsilon = 0.0125$, *etc.*

These requirements are less stringent than the requirement of 99.5% efficiency of the muon system as stated in the CDR.

2 How Can We Measure the Efficiency of the Muon System?

The ideal method to measure the efficiency of the muon system would be to turn off the Daya Bay nuclear reactors, and then count the fraction of inverse β-decay candidates that are tagged by the muon system.

However, this will not be an option at the Daya Bay site, which will have at least 3 reactor cores operational at all times.

Realizable methods for the efficiency measurement are of two types. First, "trigger" on a neutron-induced signal in the antineutrino detector that cannot come from inverse β-decay, and observe the number of muon tags for these events. Second, devise an "external trigger" on muons with an auxiliary detector system, or with part of the muon system, and observe the number of muon tags for these events. In both cases, there is the issue of whether the "trigger" properly represents the class of muons that lead to neutron-induced backgrounds.

In my opinion, this issue is particularly acute for the "external trigger" option. Inefficiencies in the muon system are most likely due to muons whose track length in the muon system is small. It is very difficult to devise an "external trigger" on such events, and also to know how to extrapolate from the measured efficiency on these difficult muons to that for all relevant muons.

Rather, it is preferable to base the efficiency measurement on a "trigger" from information in the antineutrino detectors.

The signature of an inverse β-decay is two observed depositions of energy of 1-10 MeV within a time window of ≈ 200 μs. Besides mimicking this signature, neutrons from cosmic-ray muon showers can produce events in which the "prompt" energy deposition is larger than 10 MeV, as well as events in which more that 2 energy depositions occur with a 200 μs time window.

For example, "prompt" neutron energy depositions of 10-20 MeV will occur at about the same rate as those in the range 1-10 MeV, according to a GEANT3 simulation by J. Cao as shown on the left of Fig. 2 (Fig. 3.7 of [1]). Some confirmation of this simulation comes from the CHOOZ experiment, fig. 46 of [4] shown on the right of Fig. 2; it is possible that the GEANT3 simulation underestimates the prompt neutron energy deposition below 2 MeV.

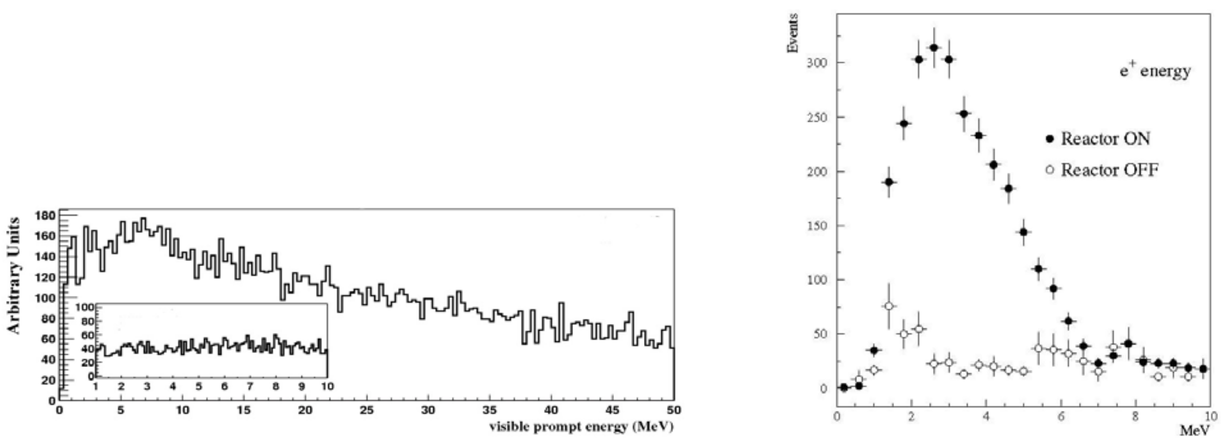

Figure 2: Left: The prompt energy spectrum of fast neutron backgrounds at the Daya Bay far detector. The inset is an expanded view of the spectrum from 1 to 10 MeV. Right: prompt energy in the CHOOZ detector with the reactor on and off, after cuts that suppress prompt energy from γ's [4].

The rate of neutron-induced background with a prompt signal of 10-20 MeV and a delayed signal of ≈ 8 MeV would be about 2/day in a 20-ton Far detector module. In, say, 100 days we would have $N = 200$ such events, which can be used as "triggers" to check the efficiency of the muon system. Similar studies can be done using the prompt signal in energy intervals 20-30, 40-50, ... MeV to explore possible dependence on the prompt energy of the muon-tagging efficiency.

The statistical uncertainty in the measurement of an efficiency ϵ with N events is,

$$\sigma_\epsilon = \sqrt{\frac{\epsilon(1-\epsilon)}{N}}\,. \tag{3}$$

Thus, if the total efficiency were $\epsilon = 97.5\%$, a measurement of this efficiency in a study based on 200 "triggers" would yield an uncertainty of $\sigma_\epsilon = \sqrt{(0.025/200)} = 0.011$, and hence, $\epsilon - 2\sigma_\epsilon = 0.953$.

A total efficiency of 97.5% requires a muon-detection efficiency of 99%, if 1.5% of the relevant muons miss the muon system, as discussed in sec. 1.

Thus, it appears that a single muon detection system in the water pool that has 99% detection efficiency, combined with measurements of that efficiency over 100 days via an appropriate neutron-based "trigger" from the antineutrino detector would meet the requirement that the total efficiency of the system be greater than 95% with 95% confidence.

My conclusion is that we should simplify the muon system to have only PMT's on the outer edges of the water pool in sufficient numbers to achieve 99% (calculated) efficiency. Measurement of this efficiency will be made with "triggers" from neutron-related background in the antineutrino detectors (rather than with auxiliary muons systems).

References

[1] X. Guo *et al.*, *Daya Bay Project Physics Proposal* (Oct. 3, 2006),
http://dayabay.bnl.gov/private/documents/cdr/tex/cdr_review.pdf

[2] Y. Wang *et al.*, *Predicting neutron production from cosmic-ray muons*, Phys. Rev. D **64**, 013012 (2001), http://kirkmcd.princeton.edu/examples/detectors/wang_prd_64_013012_01.pdf

[3] The Daya Bay Reactor Neutrino Experiment Collaboration, *Determination of Neutrino Mixing-Angle θ_{13} Using the Daya Bay Nuclear Power Facilities* (Nov. 8, 2005),
http://dayabay.bnl.gov/private/documents/cdr/workbook/DYB_proposal_v3.2.pdf

[4] M. Apollonio *et al.*, *Search for neutrino oscillations on a long base-line at the CHOOZ nuclear power station*, Eur. Phys. J. C **27**, 331374 (2003),
http://kirkmcd.princeton.edu/examples/neutrinos/apollonio_epj_c27_331_03.pdf