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Calculations of Muon Induced Backgrounds for Double Chooz

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A new neutrino experiment is planned at the Chooz reactor in France using two detectors to measure the parameter θ_{13} . Two important potential backgrounds are fast neutrons from muons hitting outside the fiducial volume, and muon induced spallation of ^{9}Li within the fiducial volume.

1. Introduction

In the presently accepted paradigm to describe the neutrino sector, there are three mixing angles (θ_{12} , θ_{23} , θ_{13}) that quantify the mixing of the neutrino mass and flavor eigenstates. The third angle, θ_{13} , has not yet been measured but has been constrained to be small by the CHOOZ reactor experiment[1]. The possibility exists for a rich program of measuring CP violation and matter effects in future accelerator neutrino experiments, which has led to an intense worldwide effort to develop neutrino superbeams, off-axis detectors, neutrino factories, and beta beams[2]. However, the possibility of measuring CP violation in the foreseeable future can be fulfilled only if the value of the neutrino mixing parameter θ_{13} is large enough. A timely new reactor experiment has excellent discovery potential for finding a non-zero value of this important parameter. In addition, a short time scale for a measurement or improved limit on θ_{13} will help long-baseline accelerator experiments better exploit their full potential.

The best current limit comes from a reactor experiment. An International Working Group has been studying the goal of carrying out an improved reactor neutrino program sensitive to $\sin^2 2\theta_{13} > 0.01$.[3] Reaching such a sensitivity at the level of better than 1% is a difficult task as it requires total systematic uncertainties at below the 1% level, something which has never been achieved in a reactor experiment. Double Chooz, with an expected sensitivity of $\sin^2 2\theta_{13} > 0.03$, is an important step in this program for two reasons: (1) there is an excellent chance for a new discovery, and (2) it is a realistic setting to learn more about backgrounds and systematic errors. A number of initiatives are being considered that could potentially improve the sensitivity by running longer with larger detectors located at greater depths[4, 5, 6, 7, 8]. These more sensitive experiments have great cost, long time scales, and are a challenging extrapolation from previous experiments. In contrast, Double Chooz can be done at modest cost and on a relatively short time scale using an existing facility. Information about Double Chooz is provided in the Letter of Intent[9]. Rates shown in this document come from that LOI.

2. Background Calculations for Double Chooz

The signature for a neutrino inverse beta decay event is a prompt signal with a minimum energy of about 1 MeV and a delayed 8 MeV signal after neutron capture in gadolinium. The process is:

$$\bar{\nu}_e + p \rightarrow e^+ + n \ . \qquad (1)$$

This may be mimicked by background events which can be divided into two classes: accidental and correlated events. The former occur when a neutron like event by chance falls into the time window (typically 100 μs) after an event in the scintillator with an energy of more than one MeV. The latter is formed by neutrons which slow down by scattering in the scintillator, deposit $>$ 1 MeV visible energy and are captured in the Gd region.

2.1 External background sources

Cosmic muons produce neutrons in the target region via spallation and muon capture. Those muons intersect the detector and should be identified by the veto systems. However, some neutrons may be captured after the veto time window. Therefore we estimate the rate of neutrons, which are generated by spallation processes of through going muons and by stopped negative muons which are captured by nuclei.

The first contribution is estimated by calculating the muon flux for different overburdens and taking into account an $E^{0.75}$ dependence for the cross section of neutron production, where E is the depth dependent mean energy of the total muon flux. The absolute neutron flux is obtained by considering measured values in several experiments (LVD[10], MACRO[11], CTF[12]) and extrapolating these results by comparing muon fluxes and mean energies for the different overburdens. Table 1 gives the expected neutron rate versus overburden.

Table 1. Estimated neutron rate in the active detector region due to through going cosmic muons.

Overburden (m.w.e.)	μ rate (s^{-1})	$< E_\mu >$ (GeV)	Neutrons through going μ (s^{-1})	μ stopping rate (s^{-1})	Neutrons stopping μ (s^{-1})
40	$1.1 \cdot 10^3$	14	2	$5 \cdot 10^{-1}$	0.7
60	$5.7 \cdot 10^2$	19	1.4	$3 \cdot 10^{-1}$	0.4
80	$3.5 \cdot 10^2$	23	1	$1.2 \cdot 10^{-1}$	0.2
100	$2.4 \cdot 10^2$	26	0.7	$6 \cdot 10^{-2}$	0.08
300	$2.4 \cdot 10^1$	63	0.15	$2.5 \cdot 10^{-3}$	0.003

Negative muons which are stopped in the target region can be captured by nuclei where a neutron is released afterward. The rate can be estimated quite accurately by calculating the rate of stopped muons as a function of overburden and taking into account the ratio between the μ-life time and μ-capture times. As the capture time in Carbon is known to be around 25 μs ($\approx$1 ms in H) only about 10% of captured muons may create a neutron. The estimates are shown in Table 1. The neutron generation due to through going muons dominates.

2.2 Beta-neutron cascades

Muon spallation on ^{12}C nuclei in the organic liquid scintillator may generate ^{8}He, ^{9}Li, and ^{11}Li which may undergo beta decay with a neutron emission. Those background events show the same signature as a neutrino event. For small overburdens the muon flux is too high to allow tagging by the muon veto, as the lifetimes of these isotopes are between 0.1 s and 1 s. The cross sections for the production of ^{8}He, ^{9}Li have been measured by a group of TUM at the SPS at CERN with muon energies of 190 GeV (NA54 experiment[13]). In this experiment the combined production of ^{8}He + ^{9}Li were obtained.

A conservative estimate of 2 events per day in the target region can be estimated for 300 m.w.e. by assuming $E^{0.75}$ scaling as we did in calculating the neutron flux. An alternative scaling has been suggested whereby the number of ^{9}Li/^{8}He-producing interactions varies in proportion to the flux of muons over 500 GeV[14], leading to a lower event rate of 0.4 per day.

In Table 7.4 of reference [9], all radioactive ^{12}C-spallation products including the beta-neutron cascades are shown with the estimated event rates in both detectors. The Q-values of the beta-neutron cascade decays is 8.6 MeV, 11.9 MeV, 20.1 MeV for ^{8}He, ^{9}Li, and ^{11}Li, respectively. KamLAND has measured that the production of ^{9}Li (lifetime 838 ms) dominates the production of ^{8}He (lifetime 119 ms) by at least a factor of 8.

2.3 External neutrons and correlated events

Very fast neutrons, generated by cosmic muons outside the detector, may penetrate into the target region. As the neutrons are slowed down through scattering, recoil protons may give rise to a visible signal in the detector. This is followed by a delayed neutron capture event. Therefore, this type of background signal gives the right time correlation and can mimic a neutrino event.

A Monte-Carlo program has been written to estimate the correlated background rate for a depth of 100 m.w.e. and a flat topology. In order to test the code the correlated background for the Chooz experiment (different detector dimensions, 300 m.w.e.) has been calculated with the program. The most probable background rate was determined to be 0.8 counts per day. A background rate higher than 1.6 events per day is excluded by 90% C.L. This has to be compared with the measured rate of 1.1 events per day. The Monte-Carlo program reproduces the real correlated background value roughly within a factor 2.

For Double Chooz we calculated the correlated background rate for 100 m.w.e. and estimated the rates for other overburdens by taking into account the different muon fluxes and assuming a $E^{0.75}$ scaling law for the probability to produce neutrons. The neutron capture rate in the Gd loaded scintillator for an overburden of 100 m.w.e. is about 300/h. However, only 0.5% of those neutrons create a signal in the scintillator within the neutrino window (i.e. between 1 MeV and 8 MeV), because most deposit much more energy during the multiple scattering processes. The quenching factors for recoil protons and carbon nuclei has been taken into account. In addition around 75% from those events generate a signal in the inner muon veto above 4 MeV (visible β equivalent energy). In total the correlated background rate is estimated to be about 3 counts per day for 100 m.w.e.. This can be measured to high precision using events tagged by the inner and/or outer veto. In Table 2 the estimated correlated background rates are shown for different overburdens.

The correlated background rates can be compared with accidental rates, where a neutron signal falls into the time window opened by a β^+-like event. The background contribution due to accidental delayed coincidences can be determined *in situ* by measuring the single counting rates of neutron-like and β^+-like events. Therefore the accidentals are not so dangerous as correlated background events. Radioactive elements in the detector materials will be carefully controlled, especially in the scintillator itself, so the beta-gamma rate above 1 MeV will be only a few counts per second. For a time window for the delayed coincidence of $\sim$200 μs (this should allow a highly efficient neutron detection in Gd loaded scintillators), and a veto efficiency of 98%, the accidental background rates are estimated in Table 3. The rate of neutrons which cannot be correlated to muons ("effective neutron rate") is calculated by $n_{eff} = n_{tot} \cdot (1 - \epsilon)$, where n_{tot} is the total neutron rate (sum of the numbers given in Table 1) and ϵ is the veto efficiency. If the veto efficiency is 98% or better, the accidental background for the far detector is far below one event per day (see following Table 3).

Table 2. Estimated neutron rate in the target region and the correlated background rate due to fast neutrons generated outside the detector by cosmic muons.

Overburden (m.w.e.)	Total neutron rate in ν-target (h^{-1})	Correlated background rate (d^{-1})
40	829	8.4
60	543	5.4
80	400	4.2
100	286	3.0
300	57	0.5

Table 3. Example of estimated accidental event rates for different overburdens. The rates scale with the total beta-gamma rate above 1 MeV (here $b_{tot} = b_{ext} + b \approx 2.5$ s^{-1}), the time window (here $\tau = 200\,\mu$s) and the effective neutron background rate. A muon veto efficiency of 98% was assumed.

Overburden (m.w.e.)	Effective neutron rate (h^{-1})	Accidental background rate (d^{-1})
40	97	2.4
60	65	1.6
80	43	1.0
100	28	0.7
300	6	0.15

Correlated events are the most severe background source for the experiment. Two processes mainly contribute: β-neutron cascades and very fast external neutrons. Both types of events are coming from spallation processes of high energy muons. In total the background rates for the near detector will be between 9/d and 23/d if a depth of 60 m.w.e. is chosen. For the far detector a total background rate between 1/d and 2/d is estimated.

3. Discussion

An outer veto is also being planned for the near detector to further reduce and characterize muon induced backgrounds. A FLUKA based Monte Carlo is being run to design the optimum parameters for the outer veto, by calculating the distributions for muons which make the relevant background neutrons. The uncertainty in correlated background rates is also being further understood by using the reactor off data from CHOOZ, and fitting the energy distribution to the expected distributions from possible backgrounds.

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