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ScienceDirect
Nuclear Instruments and Methods in Physics Research A 569 (2006) 127–131
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

Near detector at a neutrino factory

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Available online 11 October 2006

Abstract

A near detector at a neutrino factory is essential for the measurement of neutrino oscillations, by performing the ratio of neutrino interactions between the near and far detectors. The near detector needs to establish the neutrino flux, beam angle, divergence, and energy of the neutrino beam, as well as determining the polarization of the muons that produce the neutrinos. Cross-section measurements and other physics such as measurements of parton distribution functions and charm physics can also be carried out at a near detector.There are many technological choices for a near detector at a neutrino factory, but a detector comprising an active silicon target inside a magnetic field for precise vertex reconstruction, followed by muon and electron identification is capable of carrying out these goals. A prototype silicon detector consisting of four passive layers of boron carbide and five layers of silicon microstrip detectors (NOMAD-STAR) was implemented within the NOMAD neutrino oscillation experiment. Impact parameter and double vertex resolutions were measured for this detector and a sample of charm decays was reconstructed for the first time using silicon detectors inside a neutrino beam. Consequences and lessons learnt from this prototype shall be applied to the case of a near detector at a neutrino factory.

PACS: 13.15.+g; 29.40.Wk; 29.40.Gx; 13.20.Fc

Keywords: Neutrino factories; Near detector; Silicon microstrip detectors; Charm detection

1. Introduction

Neutrino oscillations are now a well established phenomenon due to the observations from atmospheric [1] and solar neutrinos [2–4] as well as reactor neutrinos [5]. The Pontecorvo–Maki–Nakagawa–Sakata (PMNS) [6,7] matrix establishes that mixing is allowed amongst the three neutrino flavours (similar to the CKM quark mixing matrix) with the intriguing possibility of CP violations in the neutrino sector. CP violation in neutrinos is the key to understanding the matter–antimatter asymmetry of the universe through the processes of leptogenesis and baryogenesis [8].

While the mixing angle for solar neutrinos has been fitted to be: $\tan^2\theta_{12} = 0.46^{+0.10}_{-0.07}$ with the mass squared difference $\Delta m^2_{12} = 8.0^{+0.7}_{-0.6} \times 10^{-5}\,\mathrm{eV}^2$, and the mixing angle for atmospheric neutrinos is maximal with $\sin^2\theta_{23} = 0.50 \pm 0.08$ and $\Delta m^2_{23} = 3.2 \times 10^{-3}\,\mathrm{eV}^2$, there are still three unknowns in the PMNS matrix. We do not know the value of θ_{13}, with $\sin^2\theta_{13} < 0.13$ at 90% C.L., we do not know the mass hierarchy between mass states and we do not know the value of the CP violating phase δ [9].

A neutrino factory from the decay of muons [10] has been proposed as the ultimate neutrino source, to be able to answer the previous three questions. A beam of protons impinges onto a target, producing pions that are phase rotated to reduce their momentum spread and increase the emittance of the beam. These decay into muons that are transported through a cooling channel to reduce the transverse emittance of the muon beam, and then accelerated to a nominal energy that is injected into a muon storage ring [11–13]. For example, if positive muons are injected, these decay in the straight sections of the ring:

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doi:10.1016/j.nima.2006.09.060

$\mu^+ \rightarrow e^+ + \bar{\nu_\mu} + \nu_e$, producing neutrinos of well-defined flavours, with kinematical properties that are easily calculable.

The neutrinos travel through the earth and interact in a far detector thousands of kilometres away, in order to observe neutrino oscillations. The oscillation "golden channel" signal [14] consists of observing ν_μ by the wrong-sign muon signature. This can be identified, for example, in a large magnetized iron calorimeter that can distinguish between muons, hadrons and electrons, and can measure the charge of the lepton. The main backgrounds for this signal are due to wrong charge identification and to the production of wrong sign muons from the decay of a charm particle (for example a D^-), where the primary muon from the charged current interaction has not been identified.

2. Near detector at a neutrino factory

To achieve the physics goals of a neutrino factory, it is necessary to establish the ratio of neutrino interactions in a near detector with respect to the far detector. Hence, the careful design of a near detector is crucial to reduce the long baseline neutrino oscillation systematic errors. To achieve this, one needs to control the neutrino flux, the beam angle, divergence, energy and the polarization of the muons that cause the decay. In addition, a near detector needs to perform a high statistics measurement of the charm signal from neutrino interactions, which is one of the main sources of background for the oscillation signal at the far detector.

There is also a rich physics programme that can be carried out at a near detector [15]. Deep inelastic, quasi-elastic and resonance scattering reactions can be studied with unprecedented accuracy. Other measurements include the determination of the weak mixing angle $\sin^2\theta_{\mathrm{W}}$ from the ratio of neutral to charged current interactions, measurements of the parton distribution functions (both polarized and unpolarized) in a region of phase space that is complementary to those determined by HERA, a measurement of the strong coupling constant and other effects such as nuclear shadowing. The large sample of charm events can be used for measurements of the CKM matrix element V_{cd}, and search for CP violation in $D^0 - \overline{D^0}$ mixing. The sign of the lepton produced at the primary vertex can be used to tag whether a D^0 or a $\overline{D^0}$ was produced, with the decay products determining whether there was any change in the flavour of the charm meson. More accurate measurements of Λ polarization might shed light on the spin content of nucleons.

This varied physics programme requires a near detector (or detectors) with high granularity in the inner region that subtends to the far detector. The active target mass of the detector does not need to be very large. With a mass of 50 kg, one would obtain 10^9 events per year at a distance of 30 m from the muon storage ring.

The detector should be able to operate at a high rate and have very good spatial resolution, to be able to distinguish primary and secondary vertices needed to identify charm events. It should also have a small radiation length so that it may distinguish electrons from muons in a magnetic field. This can be achieved by a vertex detector of low Z (either a solid state detector, such as silicon, or a fibre tracker) followed by tracking in a magnetic field and calorimetry, with electron and muon identification capabilities.

3. A prototype detector: NOMAD-STAR

A silicon vertex detector (NOMAD-STAR) was installed upstream of the first drift chamber of the NOMAD neutrino oscillation experiment [16]. The main aim of this detector was to test the capabilities of silicon detectors for $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ oscillation searches [17,18]. However, this set-up can mimic a possible design for a near detector at a neutrino factory. It was used to measure the impact parameter and double vertex resolutions to determine the charm detection efficiency. The target consisted of four layers of boron carbide (B_4C) with a total mass of 45 kg, interleaved with five layers of single–sided silicon micro-strip detectors (see Figs. 1 and 2).

The five layers of silicon detectors had a total active surface of 1.14 m^2, with 10 ladders per layer and 12 silicon microstrip detectors per ladder [19]. The ladders were the longest working silicon ladders ever built (72 cm). The sensors were Hamamatsu FOXFET p^+ on n single-sided detectors, 300 μm thick, 33.5×59.9 mm^2 wide, with strip and read-out pitches of 25 and 50 μm, respectively [21]. The 640 read-out strips per detector, parallel to the NOMAD magnetic field (x-axis), measured the y projection of the track with a point resolution of 5 μm [20]. The read-out electronics consisted of VA1 chips [22] with a shaping time of 3 μs.

4. NOMAD-STAR performance

The noise performance of the majority of the long silicon ladders was found to be as expected (noise of $1500 \pm 250\, e^-$, corresponding to a signal to noise of 17:1), with average hit-finding efficiencies above 98% [23]. About 20% of the ladders exhibited variable noise, attributed to a slow build-up of charge in between some layers. The noise in these ladders varied between 2000 and 3000 e^-, while the efficiency remained always above 92%. A Kalman filter [24] was used for tracking, vertexing and for the alignment of the silicon ladders [25]. The alignment residuals were 9 μm for the three inner planes and 12 μm for the two outer planes. After the alignment, hit residuals in the y projection had a RMS of 8.6 μm, with the y and z vertex resolution 19 and 78 μm and the y double vertex resolution (from K^0_{s} decays) 18 ± 4 μm [23].

The impact parameter (defined as the projected signed distance of the μ^-, from a ν_μ charged current, CC,