Simulation of a RICH detector for \( \tau \) neutrino appearance

T. Ekelof\textsuperscript{a,}\textsuperscript{*}, R. Forty\textsuperscript{b}, C. Hansen\textsuperscript{a}

\textsuperscript{a}Department of Radiation Sciences, Uppsala University, ISV, Box 535, SE-75121 Uppsala, Sweden
\textsuperscript{b}CERN, CH-1211 Geneva, Switzerland

Abstract

A data analysis procedure is proposed for a \( \tau \) neutrino appearance experiment in which the Cherenkov light from \( \tau \) leptons created in neutrino-nucleon interactions is imaged using an HPD-based RICH counter. In particular, the problem of eliminating the two orders of magnitude more abundant Cherenkov light from the long-lived charged particles, that originate from the \( \tau \) decay and from the neutrino interaction vertex, is treated. It is tentatively concluded that it would be feasible to reach a \( \tau \) signal detection efficiency of the order of 5–10\%.

Keywords: \( \tau \)-neutrino appearance; RICH; HPD; Background rejection

1. Introduction

Since the first indications of disappearance of \( \mu \) neutrinos in the SuperKamiokande experiment and the interpretation of this as the result of \( \mu \) neutrino oscillations, there has been an interest to understand into which other neutrino the \( \mu \) neutrino oscillates. By now there are rather strong indications that this other neutrino is the \( \tau \) neutrino, but the experimental evidence presented for this hypothesis is on the other hand rather indirect. The only way of providing direct evidence would be to observe the appearance of \( \tau \) neutrinos though the detection of \( \tau \) leptons being produced as a result of neutrino charged current interactions. Two experiments, OPERA and ICANOE, have been proposed for such observations in the CERN Neutrino beam to Gran Sasso (CNGS). A novel, alternative concept based on the observation of the Cherenkov light from the \( \tau \) lepton using a specific detector based on the RICH technique, has earlier been outlined in Ref. [1]. In the present paper we report on further, more detailed Monte Carlo simulations, using more elaborate analysis methods as compared to this first report. The analysis is however still progressing and what we present here is a report on our present understanding of the potentiality of the \( \tau \) detector concept based on the RICH technique.

2. Outline of the RICH \( \tau \) detector concept

Fig. 1 illustrates the concept of the RICH \( \tau \) detector based on the cupola optics scheme [2]. The neutrino beam is incident from the left and hits the target volume. This volume is filled with \( C_6F_{14} \) liquid which acts both as target material and as Cherenkov radiator medium. A \( \tau \) appearing from a charged current interaction of the incident \( \tau \) neutrino with a target nucleon will generate
Cherenkov light in the liquid provided the $\tau$ momentum is above the $\tau$ Cherenkov threshold which in $C_6F_{14}$ liquid is $2.3\,\text{GeV/c}$ ($n = 1.26$). After a flight path of the order of 1 mm the $\tau$ decays into one, three or five charged particles plus neutrons. The branching ratios are 17% for one $\mu$, 17% for one electron, 49% for one charged pion and 17% for three charged pions. The branching ratios of other charged-particle final states are of negligible magnitude for our purposes. The analysis reported in this paper is limited to the decay into one charged particle.

The charged decay particle of the $\tau$ will leave the radiator volume in practically all cases without decaying inside and thereby generate an amount of Cherenkov light which, due to the much longer flight path, is much larger than that generated by the $\tau$. Due to the presence of one (for a decay pion) or two (for a decay mu or electron) undetected neutrinos in the decay of the $\tau$, the charged decay-particle track will have a change of direction, a kink, with regard to the $\tau$ track.

The downstream wall of the volume consists of a spherical mirror and the upstream wall consists of a single-photon position detector. The Cherenkov light generated by the charged particles will be focussed to circular, ellipsoidal or hyperboloidal images on the photon detector area. The position of the focussed Cherenkov image is to first order a function of the radiating-particle direction only. The non-zero kink angle between the $\tau$ track and the charged decay-particle track thus implies that the Cherenkov images of the two particles do not coincide. The two images may however cross each other. Furthermore, taking into account that the focussed image-lines have a non-negligible width—due to the presence of optical and chromatic aberrations, limited photon position resolution and other effects—the overlap between the two image areas can be very large if the kink angle is small.

In the conceptual RICH $\tau$ detector discussed here the single-photon position detector is a Hybrid Photo Diod (HPD) [3] with a spherical-sector-shaped photo-cathode of 1 m diameter and 1 m radius of curvature. (HPD-prototypes presently under test have 0.12 m diameter and the feasibility of 1 m diameter HPD thus still remains to be demonstrated in practice.) The mirror has 1.5 m radius of curvature. The centers of curvature of the photo-cathode and the mirror coincide and the radial distance between the two spherical surfaces is thus 0.5 m. The volume of the $C_6F_{14}$-liquid-filled space between the two surfaces is $0.67\,\text{m}^3$. The density of the liquid is $1.67\,\text{g/cm}^3$ and one detector module thus contains a target mass of about 1.1 ton. Detector cupolas are stacked side by side in hexagonal close-packing with communicating liquid volumes (see Fig. 1) totaling 61 modules on a plane. The modeled detector set-up contains 16 such planes, inter-spaced with 16 large planar drift-chamber planes which provide position measurements of the charged particle tracks. The total target mass is ca. 1 kton.

3. The Monte Carlo simulation and analysis method

The neutrino-scattering event generator used in the present analysis is the JETTA package developed by the CHORUS Collaboration [4]. The neutrino beam momentum spectrum of the projected CNGS has been used. Quasi-elastic
(QEL) and deep inelastic (DIS) interactions have been studied separately. Only the decay channel in which the \( \tau \) decays to a \( \mu \) has been studied. As this channel is similar to that in which the \( \tau \) decays to a single charged pion, our present results could be taken to be approximately representative for 67% of the decay branching ratio. We do not include the channel in which the \( \tau \) decays to an electron in this category as the showering of the electron in the target liquid may pose extra problems. So far no simulation of the interaction of the produced particles with the target or the detector structure has been made.

The quantum efficiency of the HPD has been assumed to vary from about 0.3 at 3eV photon energy to about 0.2 at 6.5eV photon energy, dropping rapidly to zero outside this window, and the \( C_6F_{14} \) refractive index to vary from about 1.25 to 1.27 over the same range. The mirror reflectance has been assumed to be 0.95 and the radiator transmittance 1. Under these conditions there will be about 13 detected photoelectrons per millimeter track length for charged particle momenta far above the Cherenkov threshold.

The mean momentum of the CNGS beam is 17 GeV/c. Using the neutrino oscillation parameter values \( \Delta m^2 = 0.0035 \text{ (eV/c}^2) \text{ and } \sin^2(2\theta) = 1 \) only ca. 5% the \( \mu \) neutrinos coming from CERN will have oscillated to \( \tau \) neutrinos at Gran Sasso. Low momentum neutrinos have a higher probability to oscillate and the \( \tau \) neutrino momentum distribution at Gran Sasso will therefore be distorted towards lower values as compared to that of \( \mu \) neutrino beam. The momentum distribution of those \( \tau \) neutrinos that interact will then again be distorted by the momentum dependence of the neutrino interaction cross-section. The resulting incident \( \tau \)-neutrino momentum distribution for QEL and DIS events, respectively, are shown in Fig. 2. The distributions for the momentum of the produced \( \tau \), the length of the \( \tau \) track and the number of photoelectrons detected when the image is contained within a single HPD RICH detector are also shown in Fig. 2.

In Fig. 3a and b the displays of a QEL and a DIS event, respectively, are shown. The plots show the contours of the close-packed HPD photo-cathodes as full-line circles. Photons falling between the circular HPD photo-cathode areas are not detected. The mirrors (not shown on the plot) have a hexagonal periphery and are tightly packed so as cover the full area. The \( \tau \) neutrino is incident perpendicular to the plane. In the QEL event there are 6 detected \( \tau \) Cherenkov photons (marked with stars and circles), all falling inside one HPD, and 1903 detected \( \mu \) Cherenkov photons (dots) distributed over 4 HPDs. The kink angle between the two particle tracks is in this case 732 mrad and the two images are therefore well separated. In the DIS event there are 13 \( \tau \) photons and 3772 photons coming from four long-lived particles which are the \( \mu \), coming from the \( \tau \) decay vertex, and a proton and two charged pions, coming from the neutrino interaction vertex. The angles that the four long-lived particle tracks make with the \( \tau \) track are 255, 198, 643 and 647 mrad, respectively, and the images are therefore again well separated.

In the analysis, the tracks of the long-lived particles are reconstructed from the data of the external drift chambers. In the case of more than one long-lived particle track, the interaction vertex can be reconstructed as the point of closest approach between the tracks. In the case of only one long-lived particle track, the total length of the track inside the radiator, and thereby the interaction vertex, can be reconstructed from the total amount of detected light, assuming that practically all that light is emitted by the single long-lived particle. Knowing the reaction vertex, the emission polar angle of any detected photon with regard to a given track can be reconstructed under the approximate assumption that the photon is emitted from the midpoint of that track. This is done by first reconstructing the photon reflection point at the spherical mirror, using a quartic equation [5]. The input data required to solve this equation are the coordinates of the photon detection and emission points as well as the center position coordinates and the radius of the spherical mirror. The equation will provide four solutions, two of which are, in the majority of cases, complex. In the case of two real solutions, one of them always represents a reflection point in the backward hemisphere and can therefore be discarded. Having in this way determined the
mirror reflection point the photon emission angle with regard to the given track can be calculated. A plot of the emission polar angles of the ensemble of detected photons thus obtained having a unique solution, will have a distinct peak at the Cherenkov angle of the given track. For the ensemble of detected photons which have four real solutions, the solution with photon emission polar angle closest to that peak is selected. All photons actually emitted from the given track will fall in the Cherenkov peak whereas the photons emitted from any of the other tracks will spread out as a more or less flat background in such a plot.

Having identified the reaction vertex and the Cherenkov peak for each of the tracks, the Cherenkov photons of all charged particles, except those of the $\tau$, are eliminated as background in the following way. The emission polar angle of any detected photon with regard to a given track is again calculated, but this time twice, assuming that the emission point is at the start and end points, respectively, of the given track. In our simulation,
the effects of chromatic aberration are included. Half the chromatic spread in Cherenkov angle is added to the larger, and subtracted from the smaller, of these two polar angles. If the mean value of the Cherenkov angular peak of the given track falls inside the angular range between these two polar angle values, the photon is identified as having been radiated from that track and is excluded as background. Repeating this procedure for all photons and for all tracks will leave only photons emitted from the $\tau$ track. However, also some of the $\tau$ photons will, in general, be eliminated this way. In the QEL event displayed in Fig. 3a only 1 (circle) of the 6 $\tau$ photons, lying too close to the $\mu$ image, is eliminated in this way and 5 (stars) $\tau$ signal photons remain. In the DIS event display 8 of 13 $\tau$ photons are eliminated and 5 remain.

4. Intermediate results and future plans

The analysis procedure above is described for the case of a single charged long-lived particle from the $\tau$ decay. It is however equally applicable in the case of three (or even five) long-lived 

Fig. 3. Display of (a) one quasi-elastic and (b) one deep inelastic $\nu_t$ nucleon interaction as recorded by the RICH $\tau$ detector. The large full-line circles represent the HPD photo-cathode contours, the small rings and stars show the detected Cherenkov photons from the $\tau$ and the dots those from the $\tau$ decay $\mu$ and, in the deep inelastic event, from the long-lived charged particles created in the $\nu$ interaction vertex. For the interpretation of the photon patterns see the text.
charged particles from the decay of the $\tau$. The procedure has been applied to two Monte Carlo generated samples of 200 QEL events and 200 DIS events, respectively, in which the $\tau$ decays into a $\mu$ and two neutrinos. The distribution of the number of remaining detected $\tau$ photons in the two samples are shown in Fig. 4. In the QEL sample 15% of the events have 4 remaining $\tau$ photons or more and in the DIS sample, which has a higher average number of long charged tracks, this fraction is 5%. If there were to be no or very little random instrumental background from the HPDs and if, as a consequence, 4 remaining photons will be enough to provide an unambiguous $\tau$ signature, our present intermediate results indicate that the presented procedure could provide a nearly background-free $\tau$ signal reconstruction with an efficiency of the order of 5–10%.

We plan to continue this study by including one- and three-prong $\tau$ decays to charged pions and by adding to the chromatic angular error source that of the HPD pixel size. Thereafter, the GEANT simulation package will be introduced to study the effects of particle interactions with the detector material. This is particularly significant for those events in which the $\tau$ decays to an electron or in which neutral pions decaying to gammas are produced at the neutrino interaction vertex, leading to electromagnetic conversions in the liquid. The effects of delta electrons, of hadronic interactions of charged pions in the liquid, of low-energy particles stopping within the liquid volume and of charmed particles simulating $\tau$ leptons also need to be studied. It will furthermore be important to study experimentally in the laboratory and in a test beam the random noise level of the HPDs and to evaluate the minimal number of signal photons required to positively identify the $\tau$ at that noise level. To be as insensitive to such noise as possible a pattern recognition routine of the $\tau$ signal needs to be elaborated and used to limit the fiducial area within which $\tau$ photons are counted. Once this program of work has been carried out, we plan to use our thus completed simulation code to further optimize the parameters of the experimental set-up. One of the more important parameters to be tuned will be the refractive index, which can be changed by choosing fluorocarbon liquids of different density.

References