The Nuclear Emulsion Technology and the Analysis of the OPERA Experiment Data

Tsutomu FUKUDA on behalf of the OPERA collaboration
F-lab, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8602, JAPAN

OPERA is an experiment that aims at detecting the appearance of in an almost pure beam (the CNGS neutrino beam) through oscillation. OPERA is a hybrid detector that associates nuclear emulsions to electronic detectors. The nuclear emulsion provides the resolution necessary to detect CC interactions. The rst physics run started in July and ended in November 2008. In this presentation, the status of the emulsion technology and of the analysis of its data is reported.

1. Nuclear Emulsion

Nuclear Emulsion is a special type of photographic emulsion made of AgBr microcrystals interspersed in a gel matrix. A charged particle passing through such medium ionizes the crystals along its path and produces a latent image. Upon a chemical process, the development, the particle trajectory is materialized by a line of grains of metallic Ag (0.5 1 m diameter); typically the grain density is about 30 grains / 100 m (Fig. 1). Nuclear emulsion is a sub-micron 3D tracking detector with a resolution of 0.3 m. In particle physics, the nuclear emulsion technology is notably reputed for the discovery of the pion [1] and of the charm particle in cosmic-ray [2] and for the rst observation of the tau-neutrino [3].

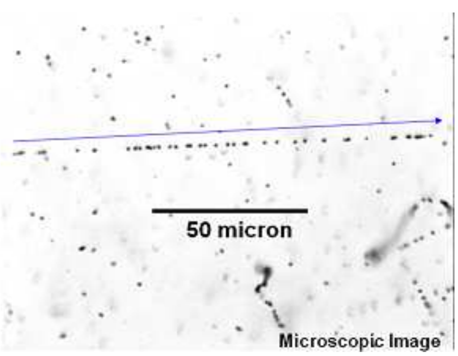

Figure 1: A charged particle track in nuclear emulsion.

2. The OPERA Experiment

In 1962, Maki, Nakagawa and Sakata proposed that oscillation may exist between massive neutrinos of different avours [4]. In 1998, the Super-Kamiokande experiment established the de cit in atmospheric due to their disappearance through the oscillation mechanism [5]. This has been con rmed later by the K2K [6] and then the MINOS [7] accelerator experiments. The goal of the OPERA experiment [8] is to detect for the rst time the appearance in a beam in the atmospheric sector. The path length of the leptons produced in CC interactions is very short (c = 87 m) thus requiring very high spatial resolution. In 2001, The DONuT experiment succeeded in detecting such interactions in Emulsion Cloud Chambers or ECC (Fig. 2).

The detector is exposed to the CERN CNGS beam with an average energy of 17 GeV, well above the lepton production threshold in CC interactions [9]. The rate of prompt is negligible at such energy. It is located in the Gran Sasso underground laboratory (LNGS) at a distance of 730km from the neutrino source. For the most probable measured values of the oscillation parameters, $m^2 = 2.4$ 10^{3} eV^2, $\sin^2 2 = 1.0$, the fraction of neutrinos having oscillated is about 1.7% . The expected number of detected CC events is about 2.5 for a nominal year of run corresponding to 4.5 10^{19} protons on target (pot). See also these proceedings [10].

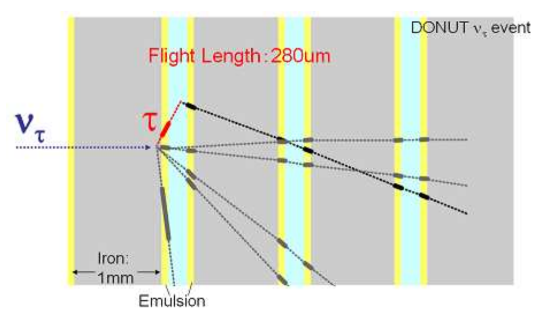

Figure 2: A tau-neutrino event detected in the DONuT experiment.

3. The OPERA Detector

OPERA is a hybrid detector composed of two identical super-modules. The targets, 1.25 kton in total, are each formed by about 75000 units called hereafter bricks based on the ECC technology. They are assembled into walls interleaved by two orthogonal planes of scintillator strips target trackers (TT) [11] used to identify the bricks in which the interactions occur. Each target is complemented by a spectrometer that identifies muons and measures their charge and momentum. An overall picture of the detector is shown in Fig. 4 and its detailed description is available in [12].

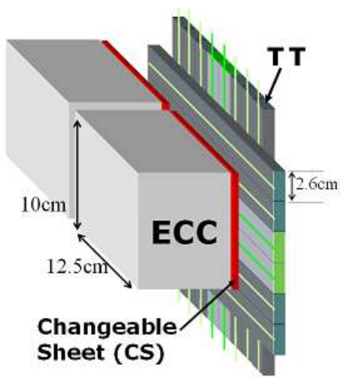

Figure 3: ECC, CS, TT.

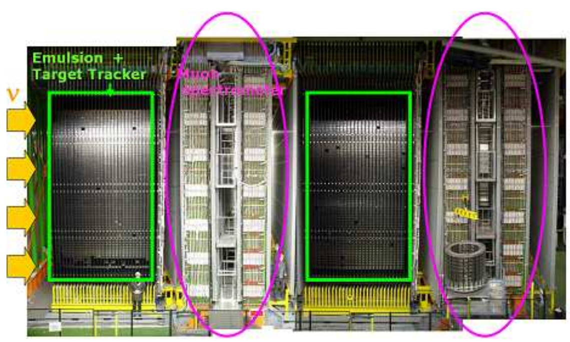

Figure 4: The OPERA Detector @ Gran Sasso (1400m underground).

The size of a brick is 12.8cm × 10.2cm × 7.9cm. It is composed of 57 0.3mm-thick emulsion films [13] interleaved with 56 1mm-thick lead plates [14]. A film has a 44 μm emulsion layer deposited on each side of a 205 μm plastic base (Fig. 5). A separate box containing a pair of films hereafter called changeable sheets or CS is glued on the downstream face of each ECC brick in front of the next TT plane (Fig. 3). They serve as interface between the brick and the TT, bringing the centimetre spatial resolution of the TT down to the μm level.

4. Flow of the event analysis

The event analysis is performed in two main steps: location of the neutrino interaction and search for a secondary vertex topology of which kinematics is compatible with that of τ decay.

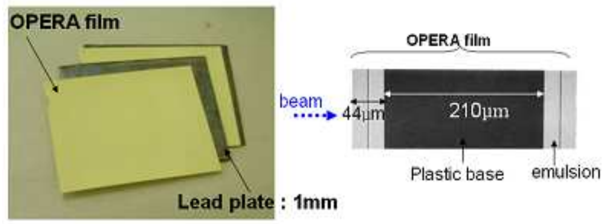

Figure 5: OPERA film.

4.1. Neutrino interactions location

The signal recorded by the electronic detectors, TT and spectrometers, is used to identify the bricks, most often one and up to 3, in which the neutrino interaction is likely to have occurred. Those bricks are extracted from the target by an automaton. The CS are removed from their box, developed and analysed, starting with the most probable brick. The level of background in the CS is negligible; essentially only tracks from the neutrino interaction are recorded. The identification of the brick is thus confirmed by finding tracks in the CS that are compatible with the electronic data, in which case the brick is disassembled and its films developed. The tracks found in the CS are extrapolated to the most downstream emulsion film where they are searched for. They are then followed back from film to film up to the location of the neutrino vertex where they disappear. Finally emulsion data is taken around this point and the neutrino interaction vertex is reconstructed.

4.2. Decay Search

The four main decay channels of the τ lepton are given in Table I. Topologically, they are classified as "kink" or "trident" if they have one or 3 charged daughters. Charm particles have similar lifetime and decay topologies as the τ lepton. Understanding their detection rate is therefore a direct verification of the expected detection efficiency of the τ lepton.

Table I τ decay modes.

topology	decay mode	ratio
kink	$\tau \to e$	18%
kink	$\tau \to \mu$	17%
kink	$\tau \to$ hadron	49%
trident	$\tau \to$ 3hadrons	15%

Single prong events fall into three categories. For 60% of the events (Fig. 6-bottom), the decay occurs inside the vertex lead plate and the parent traverses no emulsion layer. The decay products are identified by their large impact parameter (IP) with respect to the primary vertex. For 30% of the events (Fig. 6-top), the parent traverses at least one film. In this case, the trajectory of both the parent and the decay product may be reconstructed inside at least one plastic base from data registered in the two emulsion layers, the two micro-tracks, to form a base-track. The candidates are identified by the observation of a kink between both trajectories. For 10% of the events, the parent traverses only one emulsion layer and decays in the film base. There is no base track on the parent trajectory but a single micro-track. Whether the presence of this micro-track will is sufficient to identify the candidates by the observation of a kink or will it be identified by the IP method is under study.

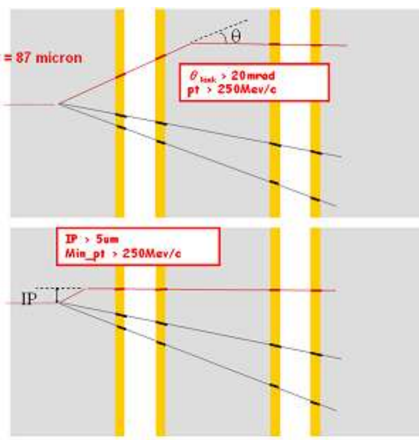

Figure 6: Decay Search.

5. Emulsion Technology developed for the OPERA experiment

5.1. The OPERA film

The mass production of the nuclear emulsion films used for OPERA is the first example of an industrial process. In the past history, nuclear emulsion film or plates were poured by hand. Machine production guarantees homogeneity in thickness and sensitivity unreachable before. An added protective coat allows hand manipulation of the film. A new feature of the OPERA film is that tracks already recorded may be erased. This process is called "refreshing".

5.2. Film refreshing

The "refreshing" process was developed to allow erasing the large background of cosmic ray tracks recorded in the films since their time of fabrication. The signal recorded in nuclear emulsion was known to fade with time at a speed depending on the environment, causing the sensitivity to track detection to progressively decrease. In the OPERA film, this fading effect is controllable. By keeping films at high relative humidity (98%) and high temperature (30 C) for 3 days, more than 99% of the recorded tracks were erased (Fig. 7) while the sensitivity to new recording is not affected. All the films were refreshed underground in the Tono mine in Japan and then transported to Gran Sasso at see level. The films used for the CS require very low background; they were refreshed a second time underground at Gran Sasso.

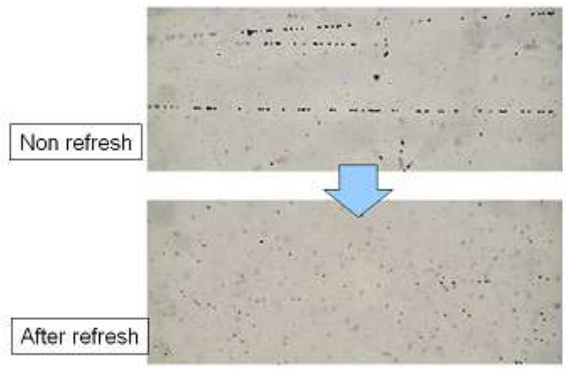

Figure 7: Film refreshing.

5.3. High speed scanning systems

The scanning area of the OPERA CS measures in cm^2; this is more than 100 times larger than for DONuT, the last experiment having used the ECC technique. Therefore high speed scanning systems were developed in both Japan and Europe. The new Japanese scanning system, the S-UTS (Super Ultra Track Selector) is shown on Fig. 8-left. Four systems with a scanning speed of 75cm^2 per hour and one of 20cm^2 per hour are operational in Japan. The previous generation operated at speeds of about 1cm^2 per hour [15]; 5 such systems are used for manual verification and subsidiary tasks. The European scanning machine [16], the ESS (European Scanning System) is shown on Fig. 8-right. It operates at a speed of 20cm^2 per hour. A total of 33 such systems are currently active for OPERA.

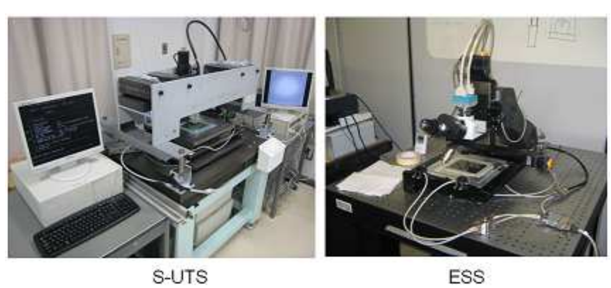

Figure 8: New Scanning Machines.

5.4. Momentum measurement in ECC bricks

The momentum of charged particles can be estimated in ECC bricks by measuring their Multiple Coulomb Scattering [17]. When a particle of charge z, momentum p and velocity βc traverses a material of depth x and radiation length X_0, the distribution of the scattering angle is expressed by a Gaussian, the RMS of which is approximately given by Eq.1.

$$\theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \qquad (1)$$

The measurement of the angle differences in two consecutive films provides the momentum estimation (Fig. 9). The results of a test experiment at KEK are shown in Fig. 10. A brick was exposed to 0.8GeV/c and 1.5GeV/c pion beams. The values of the momentum measured by MCS are respectively of 0.79GeV/c ($\Delta p/p = 11\%$) and 1.53GeV/c ($\Delta p/p = 16\%$).

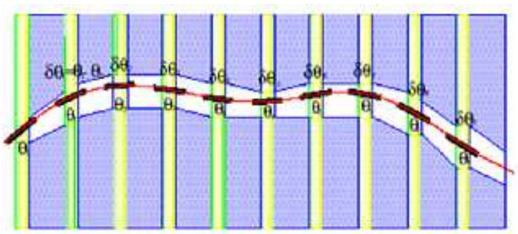

Figure 9: Momentum measurement in ECC bricks.

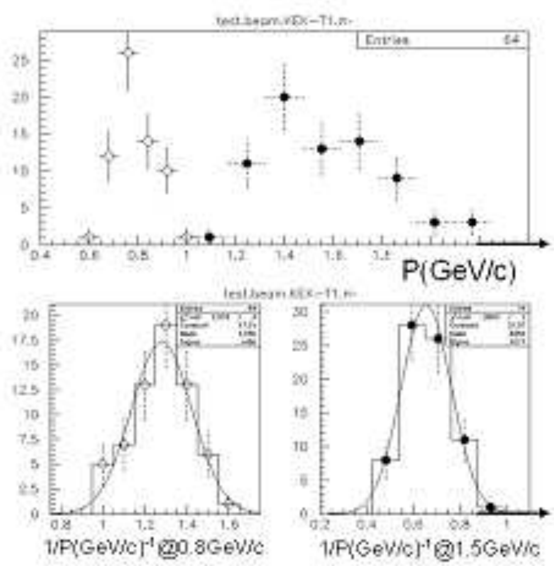

Figure 10: Result of a test experiment at KEK.

5.5. Electron energy measurement in ECC bricks

Fig. 11 shows the development of electromagnetic showers generated by electrons in an ECC brick. Counting track segments in the shower provides an estimation of the incident electron energy [18]. Fig. 12 shows the result of a test experiment at CERN with 2GeV and 4GeV electron beams. There is agreement between the measured and Monte Carlo simulated distributions of the numbers of segments though errors on data are large.

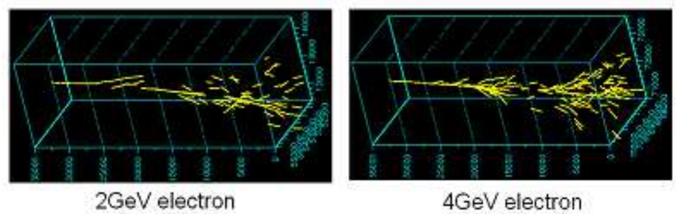

Figure 11: Electron energy measurement in ECC bricks.

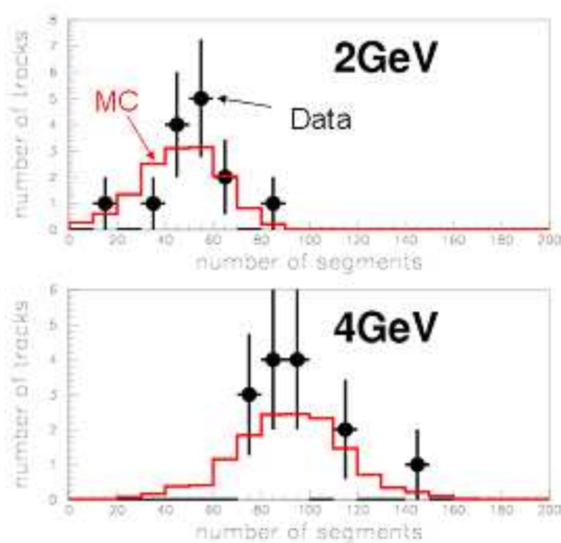

Figure 12: Result of a test experiment at CERN.

5.6. dE/dX measurement in ECC bricks

In nuclear emulsion, the grain density recorded along the track of a charged particle is almost proportional to its energy loss dE/dX (Fig. 13, [19]). ECC bricks have been exposed to 0.4GeV/c, 0.5GeV/c, 0.6GeV/c, 0.74GeV/c, 0.87GeV/c, 1.14GeV/c and 2.0GeV/c proton and pion beams at KEK. Fig. 14-left illustrates the particle identification capability of the method (pion, proton and deuteron contamination) at 0.87GeV/c. The relation between the grain density and the momentum of the particles is shown Fig. 14-right.

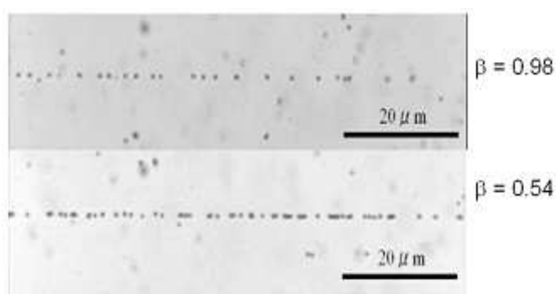

Figure 13: A pion track of 0.6GeV/c(top) and a proton track of 0.6GeV/c(bottom).

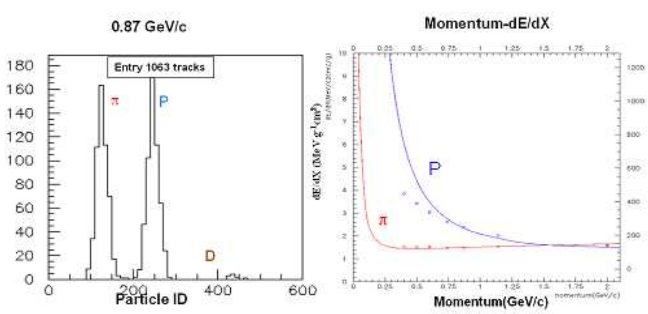

Figure 14: Result of a test experiment at KEK.

6. Status of the 2008 OPERA run

6.1. Location status

Triggers for a total of 1690 events in the target were generated by the TT in time with the CNGS beam arrival. Tables II and III summarize the current status of the events location in the CS and in the bricks after the analysis of the most probable CS indicated by the TT is well advanced. 797 events have been located already in the bricks. For events not found in the CS, the analysis of the next most probable CS has started.

Table II Current status of the event location in CS.

number of events	1473
Scanning done	1440
Found in CS	1110
Next CS : now in progress	330

Table III Current status of the event location in ECC bricks.

	NC	CC	TOTAL
ECCs received in laboratories	218	959	1177
ECCs measured	195	895	1090
CS to ECC connection successful	178	849	1027
Neutrino interactions located in the ECC	119	678	797
Neutrino interactions in the upstream wall	12	46	58
Neutrino interactions in the dead material	4	17	21

6.2. Decay search status

The search for decay vertices in the events already located is in progress. Fig. 15 shows in red the minimum distance between pairs of tracks with P > 1GeV/c emitted in real neutrino interactions. In blue, it shows the Monte Carlo distribution of the IP with respect to the primary vertex of the daughter particle of leptons decaying in the lead plate of the primary vertex. The minimum distance between all pairs of primary tracks is within 10 m. This demonstrates that the OPERA ECC bricks have enough resolution to identify decay topologies based on the IP.

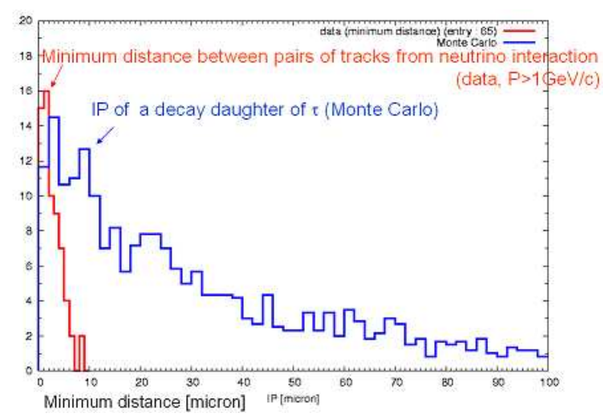

Figure 15: Distribution of minimum distances between pairs of tracks with p > 1GeV/c emitted in real neutrino interactions(red) and Monte Carlo distribution of the IP w.r.t. the primary vertex of the daughter particle of tau leptons(blue).

Some charm decay candidates have already been detected as exempli ed in Fig. 16. There are 6 tracks including a at the primary vertex. One of them decays into a $^+$ after a path length of 1330 m. The kink angle is 209mrad and the Pt of the daughter particle is about 460MeV/c. The beginning of a photon electromagnetic shower is also seen.

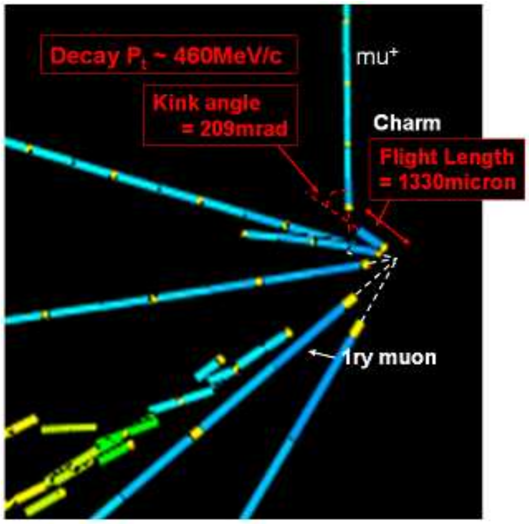

Figure 16: A charm candidate event.

7. The 2009 OPERA Run

The OPERA detector su ered no damage following the very strong L'Aquila earthquake of April 2009. The beginning of the run started on June 1 with a delay of a couple of weeks only. A nominal number of 4.5 10^{19} pot is requested from CERN, in which case about 4800 neutrino events would be collected in the OPERA targets by the end of the run and about 2.5 CC interactions would be expected to be detected.

8. Conclusions

The goal of OPERA is to detect ! oscillation in the appearance mode in the CERN CNGS beam. An innovative nuclear emulsion technology was developed for OPERA. In 2008, triggers for 1690 neutrino events in the targets were recorded. So far, the primary vertices of 797 of these events were located and analysed in the ECC bricks by a new generation of automatic scanning systems and the work is in progress. First examples of charm decay candidates were found and their kinematical analysis performed. The 2009 run has started on June 1 2009. It should lead to the potential detection of a couple of CC interactions.

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