PROCEEDINGS OF SCIENCE

Hands on Nuclear Emulsion Detectors: Scanning with Automatic Microscopes and Data Analysis

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In this paper, after a brief description of the nuclear emulsion technique and of the principles of the read-out system, we report the detector characterization in terms of spatial and angular resolution and detection efficiency. Nuclear emulsions are currently used in particle physics such as in the neutrino experiment OPERA, as well as for geophysical and medical applications.

Gran Sasso Summer Institute 2014 Hands-On Experimental Underground Physics at LNGS - GSSI14,
22 September - 03 October 2014
INFN - Laboratori Nazionali del Gran Sasso, Assergi, Italy

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1. Introduction

The first notable use of the emulsion technique dates back to 1896, when Becquerel discovered radioactivity [1]. Half a century later, Powell solved the mystery of Yukawa meason with an emulsion detector exposed to cosmic rays to detect pion decaying into muon.[2]

A major breakthrough followed with the introduction of the Emulsion Cloud Chamber (ECC) detector[3], a sandwich-like structure made of passive material layers and emulsion films: with this design emulsion-based detectors became a high-resolution tracking devices with 3-dimensional track reconstruction capabilities.

In the 1960s accelerators started to replace cosmic rays as sources of high energy particles, and fast-response detectors, such as counters and spark chambers, started to replace cloud chambers and nuclear emulsions. However, because of their unique sensitivity to resolve particle tracks less than 1 μm long, nuclear emulsions are still the ideal device to detect short-lived particles.

Nuclear emulsions are successfully used nowadays, especially in neutrino experiments: they were employed in experiments like WA17 at CERN (1979) [4], aiming at the search for charmed particles in neutrino charged current interactions, or E531 at Fermilab (1986) [5], aiming at the measurement of charmed particle lifetimes in neutrino interactions, or WA75 at CERN (1992) [6], searching for beauty particle production by a 350 GeV π^- beam.

Furthermore, the use of nuclear emulsions allowed the first (and still unique) detection of ν_τ neutrinos by the DONUT collaboration (2001) [7]. The technique of nuclear emulsions has a large scale application in the target of the CHORUS experiment (1997) [8] in which the automatic scanning of a large sample of events has first been applied. This technique has been further improved in OPERA leading to the much larger scale of the OPERA target.[9]

2. The Nuclear Emulsion Technique

Nuclear emulsion is a photographic-like film serving as a tracking detector of charged particles. Among all the tracking materials used in particle physics, nuclear emulsion features the highest position and angular resolution.

In analogy with photographic emulsion, nuclear emulsion consists of silver bromine crystals with a small mixture of iodine embedded in gelatine matrix. When an ionizing particle pass through, the emulsion, electron-hole pairs are created in the crystal. The excited electrons are trapped in the lattice defects on the surface of the crystal and silver metal atoms are created, which act as latent image centers.

After a chemical treatment called development, the latent image is enhanced and made visible : the track left by the particle results in a sequence of silver grains and can be read-out by using the optical microscopy.

Nuclear emulsion differs from common photographic emulsion films by a thicker gelatin layer, smaller size of developed silver grains to get a better single grain resolution, and a larger fraction of silver halide to gelatin, resulting in a higher sensitivity.[10]

3. Read-out System

As explained in the previous paragraphs, the read-out of a nuclear emulsion is performed by

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using the optical microscopy. Currently, fully automated high-speed scanning systems are used to perform data acquisition: the automation of emulsion scanning was pioneered by the group of Nagoya University (Japan) and the first application of an automatic system was used for the DONUT and CHORUS experiments.

For the analysis presented in this paper the European Scanning System (ESS), operating at a scanning speed of 20 cm^2/h, was used.[11][12][13]

The LNGS scanning station is currently endowed with 13 ESS mainly used for the sscanning of the emulsions of the OPERA experiment. The ESS is based on a motorised stage, holding the emulsion film, and on an optics equipped with a CCD camera, moving along the vertical direction and focusing different depths in emulsion.

The emulsions used for the analysis presented here are made of two 44 μm-thick layers on both sides of a 205 μm-thick plastic base.

By adjusting the focal plane of the objective lens through the whole emulsion thickness, a sequence of equally spaced tomographic images of each field of view are taken, processed and analysed in order to recognise aligned clusters of dark pixels called grains produced by charged particles along their trajectories. The three-dimensional structure of a track in an emulsion layer, the so-called *micro-track*, is reconstructed by combining clusters belonging to images at different levels and searching for geometrical alignments. Each micro-track pair is connected across the plastic base to form the so-called *base-track*. This strongly reduces the instrumental background due to fake combinatorial alignments, thus significantly improving the signal to noise ratio, while increasing the precision of track angle reconstruction by minimising distortion effects.

4. Resolution and Efficiency Estimation

4.1 Threshold set-up

After the scanning, images are converted to a grey scale of 256 levels where 0 is black and 255 is white. We obtain the real image by convolving the real object distribution with a point spread function (PSF) which gives the 3D distribution of the light intensity due to a point-like obstacle. A 2D Finite Impulse Response (FIR) filter is applied to enhance contrast. The image is then binarized and pixels with gray level values that exceeds a given threshold are classified as black, the remaining ones as white.

The ESS is based on an optical microscope working with transmitted light: the light source is placed under the stage, holding the emulsion film, thus resulting in a higher luminosity on the bottom emulsion layer than on the top layer. Therefore due to the not uniform distribution of the light between top and bottom emulsion layers, the threshold value has to be properly setted in order to ensure the same cluster number on both layers.

Fig. 1 shows the number of clusters obtained as a function of the threshold value for top (black line) and bottom layer (red line) respectively. The final thresholds are then set to 780 (a.u.) for top and to 700 (a.u.) for bottom layer, in a region were the number of acquired cluster is high enough to ensure a low background level while not spoiling the tracking efficiency.

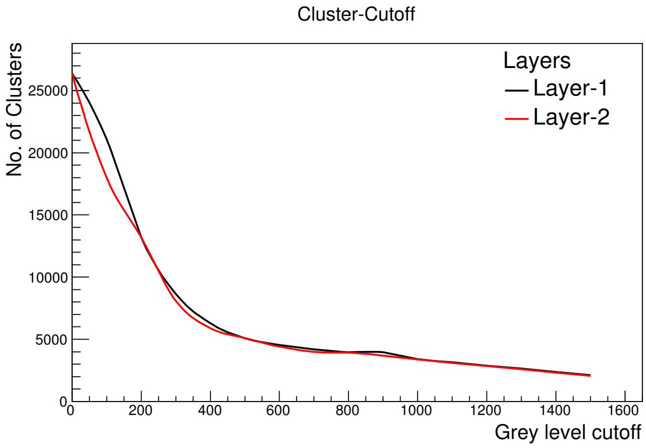


Figure 1: Number of clusters obtained as a function of the threshold value for top (black line) and bottom layer (red line) respectively.

4.2 Tracking Algorithm

Binarized images are transferred to the host PC memory and processed by a fast algorithm. Adjacent pixels above threshold are grouped together to form clusters. For each cluster, the area and the position of its centre of gravity are saved. These information are then used to perform the tracking.

For each emulsion layer grains are first connected to form the so called micro tracks. Then, the micro tracks belonging to two different layers on the emulsion are connected across the plastic base to form the so-called base tracks.

For each plate of an emulsion stack, base tracks are connected to form *volume tracks* within given position and angular tolerances. The relative alignment between the emulsion films can be obtained exploiting different methods: the use of X-ray marks allows to perform a coarse alignment with a precision of 10 μm. A fine alignment, with a precision of 1 μm, can be obtained exploiting Compton electron tracks originated by natural radioactivity or cosmic ray tracks recorded during a dedicated exposure.

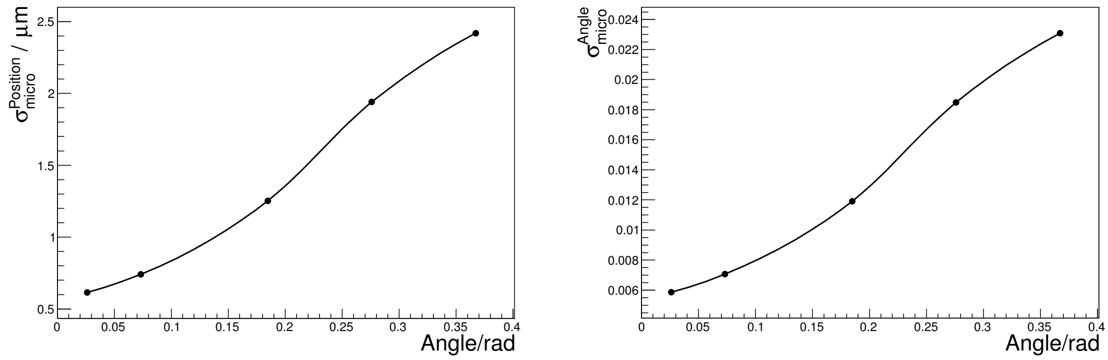
4.3 Spatial and Angular Resolution

In order to evaluate the spatial and angular resolution of an emulsion-based detector, we used a stack of emulsion plates exposed to a 10 GeV π beam.

Fig. 2a and Fig. 2b show the resolution of the micro-tracks in position and angle respectively as a function of the reconstructed track angle.

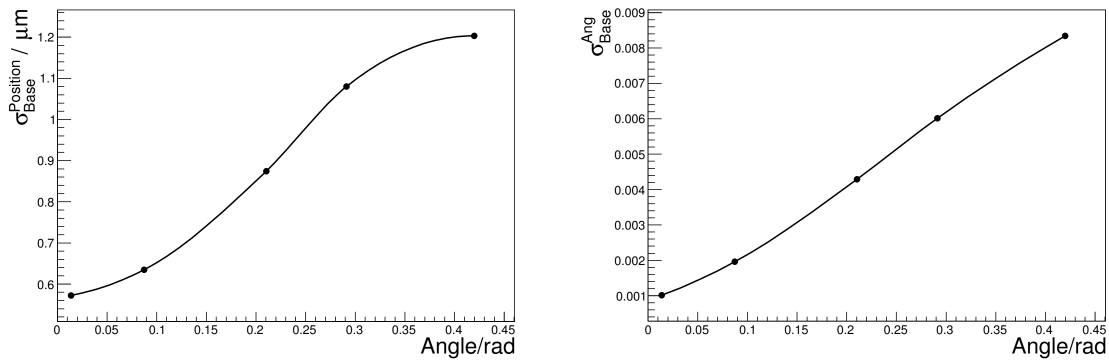
As shown in Fig. 3a and Fig. 3b, the resolution improves when we consider the reconstructed base track. In this case we obtain a resolution of less than 1 μm in position and about 1 mrad in angle for perpendicular tracks. As expected the resolution is spoiled for large angle tracks.

As expected, the spatial and angular resolution are related to the track angle. For small angles, the resolution is better. Moreover, the resolution improves using base-tracks instead of micro-tracks.



(a) Position Resolution (b) Angular Resolution

Figure 2: Position and angular resolution of reconstructed micro tracks as a function of measured angle.



(a) Position Resolution (b) Angular Resolution

Figure 3: Position and angular resolution of reconstructed base-tracks as a function of measured angle.

4.4 Efficiency

In order to evaluate the base-track reconstruction efficiency, a 2×2 cm^2 area was scanned on 5 emulsion sheets belonging to the stack exposed to the 10 GeV pion beam; the procedure illustrated in the previous section was applied and the volume-track reconstruction was done. For each emulsion sheet, the efficiency was defined as the number of passing through tracks that were measured in the sheet with respect to the total number of passing through tracks.

The obtained efficiencies and their errors are shown in Fig. 4 as a function of the angle considering 3, 4 and 5 plates of the stack respectively. The average efficiency is around 87% reaching 92% for small angle tracks.

5. Other Applications

The nuclear emulsion technique has been widely applied in particle physics, and, recently,

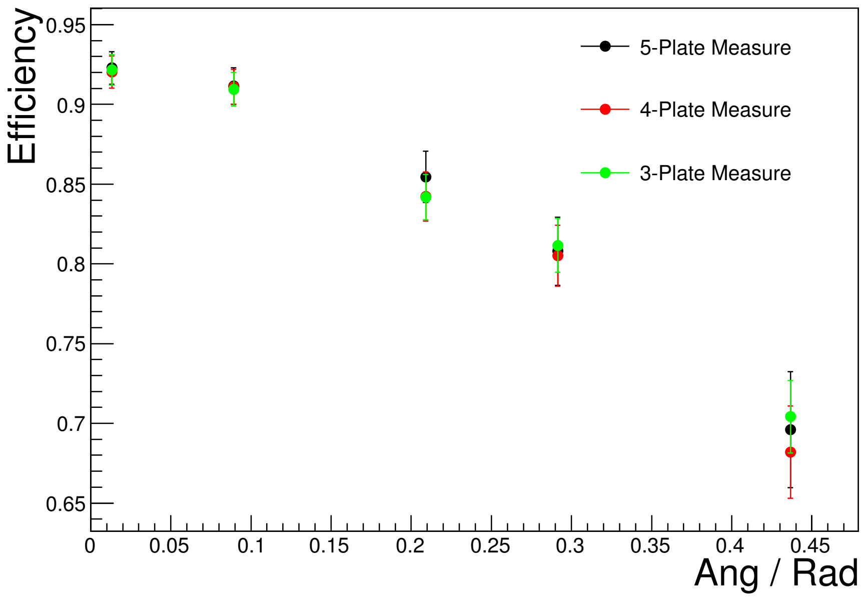


Figure 4: Efficiency as a function of track angle.

thanks to its high spatial resolution and taking advantage of the development of automated high-speed read-out systems, new perspectives are opening in this field.

In the dark matter sector, the Nuclear Emulsion WIMP Search (NEWS, [14]) project is a recently proposed directional dark matter experiment, using newly developed emulsion with spatial resolution of about 100 nm.

Nuclear emulsion detectors can also be used in geophysics for the study of the magma chamber of volcanoes exploiting the technique of the muon radiography.[15][16] Recently, tomographical emulsion detectors were used for the Unzen (Japan), Stromboli (Italy), Teide (Spain) volcanoes.

In the medical field, nuclear emulsions can be used to study the fragmentation of nuclei used in the hadron therapy when they interact with the human body, to evaluate their energy deposition and the damage to the tissues neighbouring the tumour.[17]

6. Summary

In this paper we described the main features of nuclear emulsion detectors. Then we summarized the process of data acquisition in emulsion detectors, including optical scanning and tracking algorithm. The detector and algorithm performances have been evaluated: the spatial resolution is up to 0.5 μm, the angular resolution is up to 1 mrad while the efficiency is around 87%.

Nuclear emulsions have been widely used in particle physics as well as for geophysics and medical applications.

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