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A new scanning system for alpha decay events as calibration sources for range-energy relation in nuclear emulsion

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ABSTRACT

A new scanning system named “Vertex picker” has been developed to rapid collect alpha decay events, which are calibration sources for the range-energy relation in nuclear emulsion. A computer-controlled optical microscope scans emulsion layers exhaustively, and a high-speed and high-resolution camera takes their micrographs. A dedicated image processing picks out vertex-like shapes. Practical operations of alpha decay search were demonstrated by emulsion sheets of the KEK-PS E373 experiment. Alpha decays of nearly 28 events were detected in eye-check work on a PC monitor per hour. This yield is nearly 20 times more effective than that by the conventional eye-scan method. The speed and quality is acceptable for the coming new experiment, J-PARC E07.

1. Introduction

Nuclear emulsion is used to produce special photographic films that make the tracks of charged particles visible. The emulsion consists of silver halide crystals dispersed in gelatin medium. After photographic development, silver grains are formed along the path of a charged particle passing through the emulsion layer. Then, tracks of charged particles are observed as sequences of black dots or black lines in the transparent medium through an optical microscope. The three-dimensional structure of the tracks is reconstructed from cross-sectional micrographs with sub-micrometric accuracy.

The emulsion is a very suitable detector to investigate double-Λ hypernucleus. The double-Λ hypernuclei are exotic nuclei made up of two Λ hyperons in addition to nucleons. The fine spatial resolution of emulsion makes decay chains of double-Λ hypernuclei visible. The first double-Λ hypernucleus was observed in emulsion that had been exposed to cosmic rays via a capture reaction of Ξ^- hyperon [1,2]. Moreover, two experiments with the emulsion irradiated by K^- meson beam were carried out to study double-Λ hypernucleus, i.e. KEK-PS E176 and E373. The existence of the double-Λ hypernucleus was confirmed among nearly 80 Ξ^- hyperon stopping events in the E176 experiment [3,4]. Seven events of double-Λ hypernuclei were also detected among the nearly several hundreds Ξ^- hyperon stopping events in the E373 experiment [5–7].

Detection and mass measurement of double-Λ hypernuclei are unique experimental approaches to extract the information about the Λ-Λ interaction. The Λ-Λ interaction is important for the unified understanding of Baryon-Baryon interaction, which is a fundamental concept of various nuclear phenomena in nuclear physics. The interaction is interesting to astronomical physics with respect to the inner structure of neutron stars [8].

To perform a kinematical analysis for the mass reconstruction of double-Λ hypernuclei, a range-energy calibration is quite essential. The kinetic energy of a charged particle is obtained from the range, which is the moving distance of the particle in the emulsion. The range depends not only on the particle energy but also on the emulsion density. The measured range must be corrected in depth direction because the thickness of an emulsion sheet is reduced to about a half of the original one after the photographic development.

As the calibration sources for the range-energy relation, we use decay alpha particles, which have monochromatic kinetic energies originated from natural isotopes of Thorium and Uranium in the emulsion. Their alpha decay chains produce typical topologies that can be seen in Fig. 1. Black lines are the tracks of alpha particles. The track range of a decay alpha particle is less than about 50 μm. After making the sheet, those tracks are continuously recorded until photographic development.

2. A new method for alpha decay search

We have been developing a new search method to speed up the detection of alpha decay vertices. The work has been performed by

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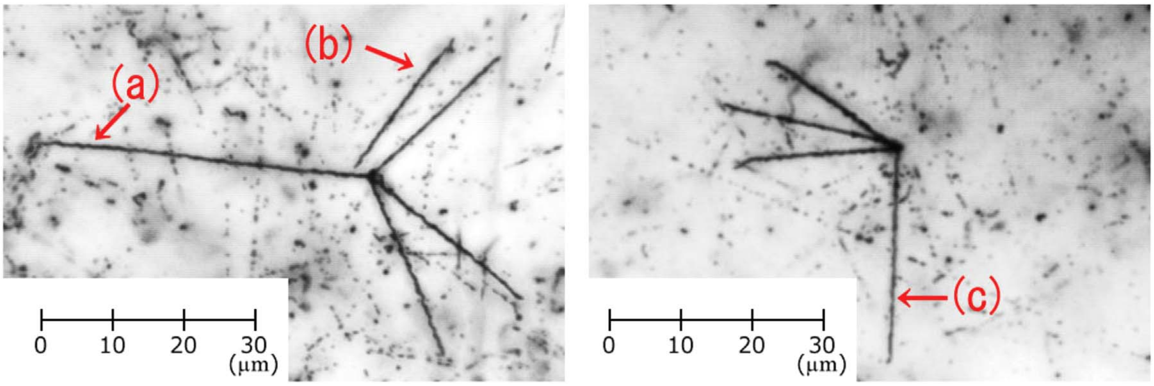

Fig. 1. An alpha decay event of Thorium series showing 5 black tracks (left) and Uranium series showing 4 black tracks (right). In the left picture, the longest track (a) is the decay alpha particle from ^{212}Po having the largest kinetic energy in the Thorium decay chain. The one (b) that is isolated from the other 4 tracks is from ^{228}Th. In the right picture, the longest one (c) is from ^{214}Po having the largest kinetic energy in the Uranium decay chain.

conventional scanning with human's eyes, so-called eye-scan, under a microscope. It is necessary to collect one hundred events of alpha decays in order to calibrate range-energy relation for a special event. It is important to expose the emulsion sheets to the beam and develop them as soon as possible after the sheet has been made, since cosmic rays and Compton electrons by gamma rays from environmental radioactive materials are recorded as tracks, which cause worse visual quality in the emulsion. By this condition, the number of alpha decay events should be very small in the emulsion. Therefore one took half to one hour to find an alpha decay event with eye-scan. This conventional search is heavy labor for the scanner and time-consuming method.

The coming experiment named J-PARC E07 aims to detect nearly one hundred double-Λ hypernuclei to obtain conclusive knowledge on Λ-Λ interaction in nuclei [9]. In order to analyze these double-Λ hypernuclear events in nearly one year, we should collect one hundred alpha decays every about four days, and then new searching method with less work load is necessary.

In the new searching method, a computer-controlled microscope scans the emulsion layers exhaustively. Image taking of the tracks under the microscope is performed by a high-speed, high-resolution camera. A dedicated image processing procedure is applied to take images and pick out vertex-like shapes, consisting of several ”black tracks” made of close unresolved grains, looking very dark. We named the method as ”Overall scanning” because this method scans the entire volume of emulsion sheets.

The specification and condition of our emulsion sheets are unique. The thickness of the emulsion layers is about 500 μm on both sides of a transparent polystyrene film with 40 μm thickness to record hypernuclear events in 4π solid angle. In these sheets, hadron beams such as π^- and K^- meson punch through vertically at a density of 10^6 tracks/cm^2. Some beam particles collide with nuclei in the emulsion, and emit nuclear fragments and several kinds of particles. Due to the dense tracks, micrographs in the deep part of emulsion is hazy. Furthermore, the range of an alpha track is within 50 μm.

In this respect, our system should be different from other automated track selection systems. Some other groups reported emulsion readout system [10,11] and tracking algorithms for large solid angle [12–14]. However, these readout systems are mainly applied to detect enough high energy particles to punch through several thin emulsion films. Besides, the track density is controlled so as not to make misconnections of tracks or to process the image processing in practical time. Table 1 describes the specification of our emulsion and those of some neutrino experiments applied by automated vertex detection. Our searching system, therefore designed anew to detect tiny alpha decay vertices in extremely dense tracks in thick emulsion sheets compared to the readout systems of DONUT [15], CHORUS [16], and OPERA [17] experiment.

2.1. Fast image taking by a 20x objective lens

We use a dedicated microscope with a large size stage for emulsion readout as shown in Fig. 2. We named this system as ”Vertex Picker”. The stage is driven by computer-controlled motors at micro-meter precision. The movable range of the stage is 40×40 cm^2. An optical microscope is mounted on a robust frame, which limits vibrations. An illuminating apparatus with 5W LEDs is used as a light source instead of incandescent bulbs to prevent thermal damages for the emulsion.

One of the key technologies is a high speed three-dimensional scanning. Under a microscopic view, a thin volume in an emulsion layer is projected to a two-dimensional image. This area and thickness are determined by the magnification of the objective lens and the field depth of the optics. By moving the horizontal axes of the stage and the vertical optical axes, three-dimensional track information is taken as a series of cross sectional images.

The microscope was therefore designed specifically for the fast three-dimensional scanning. The magnification of the objective lens is 20x and the numerical aperture is 0.35. A microscopic image is projected to a CMOS sensor through a 0.5-power reduction optical system to adjust proper pixel to μm ratio (~0.5 μm/pixel). The focal depth being nearby 6 μm is equal to about 18 μm thickness of emulsion before development, when we correct for the optical path length and shrinkage of the emulsion layer. The area of the field of view (FOV) is 1140 μm × 200 μm. The image sensor is a CMOS camera with the resolution of 2048×358 pixels and the frame rate of 800 frames per second. The diameter of a developed grain in the emulsion corresponds to approximately 1 pixel in the micrograph. In Fig. 3, 2 micrographs are shown. The larger one is taken by the Vertex Picker and the smaller one is by a scanning system for the E373 experiment with a CCD camera and a 50x lens as the comparison target.

The scanning system takes a sequential image by moving the optical system along optical axis (Z-direction) with 6 μm pitches, automatically. At the end of the image taking for a view, the FOV shifts to the next view with an overlap of 20 μm. The process is repeated until the completion of the scanning. During the scanning, surface recognition and brightness adjustment are performed automatically every 1 mm^2 for uniform image taking. The images taken are saved in an external data storage device.

2.2. Image processing

An image processing picks out vertex-like shapes among cross sectional images of the emulsion. The parameters of the image processing are tuned by emulsion sheets of the E373 experiment to detect alpha decay vertices with a reasonable Signal-to-Noise ratio.

The first step is grain enhancement and binary thresholding, which are shown in Fig. 4. We use an algorithm called “difference of