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Development of emulsion track expansion techniques for optical-microscopy-observation of low-velocity ion tracks with ranges beyond optical resolution limit

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Abstract

We succeeded to observe tracks of low-velocity Kr ions, having originally ranges below optical resolution, in a fine grain nuclear emulsion with an optical microscope after expanding the emulsion along the incident direction. This opens up the possibility of tracking low-velocity nuclear recoils from massive dark matter particles using optical microscope scanning systems.

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Keywords: Dark matter; Low-velocity ion; Nuclear emulsion

1. Introduction

Nuclear recoils from weakly interacting massive particles [1], a candidate for dark matter, can be recorded in a fine grain nuclear emulsion, or Nano Imaging Tracker (NIT) [2]. Electron microscope images of the NIT, exposed to Kr ions with velocities of interest for the dark matter detection, observed the tracks that consisted of multiple developed-grains and had ranges of a few hundreds of nanometers. Optical image discrimination between such tracks and random noise thought to be single grains, called fog, was almost impossible. In a realistic dark matter search experiment, analyzing an emulsion volume of at least 10 l is required, but electron microscopy cannot do this in a realistic time. On the other hand, automated optical microscope scanning systems [3], which have been intensively developed for neutrino experiments, are powerful tools for recognizing and measuring particle tracks. The scanning speed of the latest system corresponds to about 10 l/year/system.

Here we consider the possibility of optical imaging of very short tracks after using a technique that expands the NIT emulsion. It is known that emulsion reversibly expands and shrinks. For example, moist emulsion in a typical application is 5–10 times thicker than the dried one. When it dries, gelatin polymer fibers strongly fold back on themselves. Despite such a thickness change in a development procedure, the linear precision of developed-grains along a fast particle track has a resolution of a few tens of nanometers. Thus emulsion can expand maintaining the relative positions of the grains. These facts imply that effective expansion of the NIT after development may enable lengthening of short tracks and optical recognition of the lengthened tracks. This paper reports on NIT emulsion expansions by drawing with a roller and by swelling and results of optical imaging of low-velocity Kr tracks.

2. Track expansion by uniaxial drawing of emulsion

Expansion of the NIT emulsion with an original thickness of 20 μm was tested using optical imaging of tracks parallel to the plane of the emulsion layer. The emulsion film used for this test was horizontally exposed to

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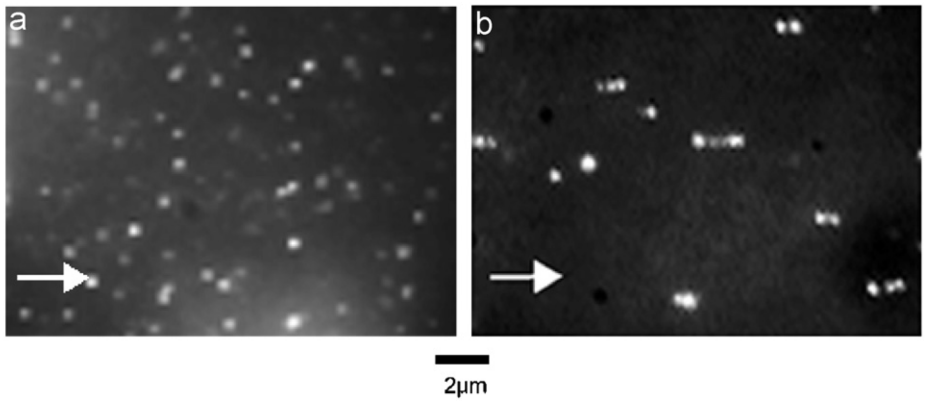

Fig. 1. Optical microscope images of the NIT exposed to 600 keV Kr ions (a) before and (b) after expansion. Arrows indicate the Kr incident direction.

a beam of 600 keV (1180 km/s) Kr ions by an ion implanter and was coated with gelatin to protect the tracks on the emulsion surface from defluxion for following expansion procedures. For development the emulsion was soaked in 7 wt% sodium sulfate presoaker for 10 min, ascorbic acid type developer [4] (Fujifilm developer for OPERA experiment (PD-T) added with RD-S) for 10 min, 5% acetic acid stopper for 10 min, FUJIFIX for 30 min, and flowing water for washing. After the development the emulsion layer was stripped off from its base. The emulsion having cross-linkages of the gelatin polymer network was hardened by the fixing solution. Soaking the emulsion in a high pH (alkaline) or low pH (acidic) solution could change characteristics of the macromolecular strands. The emulsion was soaked in a citric acid solution (pH 3) and then soaked in a glycerin solution as a viscosity improver. Subsequently, it was put in a high-temperature (40 °C) and high-humidity (95%) environment for several hours to get a higher viscosity. These procedures were used to enable the gelatin polymer network to flow somewhat under pressure without its macroscopic break. Such a plastic deformation was due to the low pH. The emulsion sandwiched between plastic films was rolled along the Kr incident direction. Areas of the emulsion, before and after a 5 times expansion along the incident direction and an unintentional 2 times expansion along the lateral direction, were observed under a dark-field optical microscope with $100\times$ objective lens as shown in Fig. 1. While only point images are seen before expansion, tracks along the Kr incident direction are clearly recognized after expansion. This method does not significantly change the emulsion volume as the emulsion layer gets thinner.

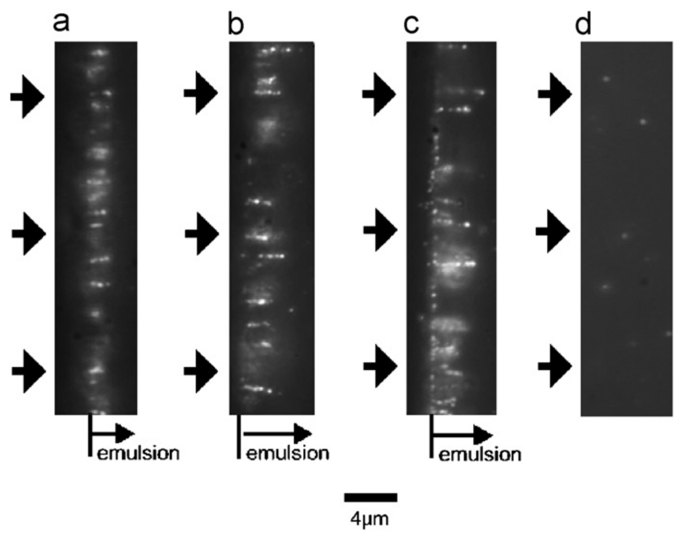

Fig. 2. Optical microscope images of cross-sections of the expanded NIT with tracks due to (a) 200, (b) 400, and (c) 600 keV Kr ions. Arrows indicate the Kr incident direction. For comparison, figure (d) shows some single grains of fog inside the emulsion layer. Single grains on the emulsion surface, shown in figure (c), are surface fog.

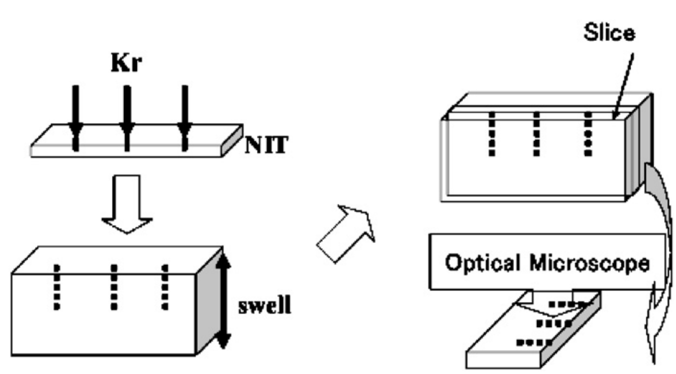

Fig. 3. Schematics of Kr ion exposure, swelling, slicing, and cross-section imaging with optical microscopy.

3. Track expansion by swelling emulsion

The drying process governs the dimensional change for tracks perpendicular to the plane of the emulsion layer. So a process that controls swelling in this direction can enhance optical imaging of very short tracks. This swelling procedure began by pouring the NIT emulsion solution into a frame on a plastic base. The frame was removed just after the emulsion set. The emulsion layer thickness of 600 μm decreased to 130 μm after drying. Areas of the emulsion film were exposed to 200, 400, and 600 keV