Oxide ceramics with fluorite structure have potential applications in the field of nuclear-technology, such as to inert matrix fuels and transmutation targets, because of their exceptional resistance to radiation damage with energetic particles. In the environment of those fuel/target applications, high-density electronic excitation will be induced along the path of fission fragments, resulting in the formation of columnar defects of ion tracks. Understanding of the atomic structure of ion tracks is indispensable to clarify the microstructure stability of the fuel/target materials under the radiation environment. This paper reports the atomic structure of ion tracks in CeO₂ exposed by high-density electronic excitation under the irradiation of swift heavy ions through atomic-resolution HAADF- and ABF-STEM observations.

Sintered polycrystals of CeO₂ specimens were irradiated with 200 MeV Xe ions at Tandem accelerator facility in Japan Atomic Energy Agency (JAEA) at an ambient temperature to fluence ranging from 3×10¹¹ to 1×10¹⁴ ions⋅cm⁻². High-density electronic excitation, whose electronic stopping power is 30 keV/nm, is induced at the surface region of specimens, at which microstructure observations were performed in the present study. Imaging and analytical TEM and scanning TEM (STEM) techniques were applied to the ion-irradiated specimens by using JEOL ARM-200F at HVEM Laboratory of Kyushu University to understand the structure of ion tracks in an atomic scale.

A low-magnification HAADF-STEM image in ceria from an end-on direction shows black-dot contrast of ion tracks as shown in Fig. 1. A line analysis of the signal intensity reveals that the atomic density of Ce cations inside the ion tracks decreases significantly. A high resolution HAADF-STEM image of an ion track in ceria (Fig. 2) shows that the crystal structure of Ce-cation column is retained even at the core region of ion tracks. It is also noted that the base-line signal intensity increases especially around the core damage region of the ion track for a size of about 4nm. An ABF-STEM image of the identical ion track shown in Fig. 2 showed that O-anion columns is preferentially blurred and/or disappeared at the core damage region of the ion track. An intensity profile across the ion track shows that the intensity of the O-anion signal is significantly reduced at the core damage region for 4 nm in diameter. Those results clearly show that the oxygen sublattice in fluorite structure is significantly disordered at the core damage region of ion tracks. The atomic structure of ion tracks implies the formation of vacancies or small vacancy clusters inside the ion tracks.

Acknowledgement: This work was partly supported by a Grant-in-Aid for Scientific Research (C) (#25420692) by Japan Society for Promotion of Science.
Fig. 1: Low magnification HAADF-STEM image of CeO\(_2\) irradiated with 200 MeV Xe ions to a fluence of 1×10\(^{14}\) ions⋅cm\(^{-2}\), which was taken from the ion-irradiated direction to show ion tracks from an end-on condition.

Fig. 2: High resolution HAADF STEM image of CeO\(_2\) taken from the [001] direction including an ion track (located at the center of the micrograph) formed under 200 MeV Xe ion irradiation to a fluence of 3×10\(^{12}\) ions⋅cm\(^{-2}\). Inserted is an atomic model of CeO\(_2\) superimposed on the HAADF-STEM image from the [001] direction.

Fig. 3: ABF-STEM image for the identical region shown in Fig. 2 (a). Magnified images of the peripheral region (b) and the core damage region of the ion track (c) are also presented.