Radiation Measurements 45 (2010) 1000–1013

Contents lists available at ScienceDirect

Radiation Measurements

journal homepage: www.elsevier.com/locate/radmeas

Measurement of track opening contours of oblique incident ^{4}He and ^{7}Li-ions in CR-39: Relevance for calculation of track formation parameters

D. Hermsdorf*, U. Reichelt

Department of Physics, Institute for Nuclear and Particle Physics, Working Group for Radiation Physics, Technische Universität Dresden, Helmholtzstr. 10, D-01069 Dresden, Germany

ARTICLE INFO

Article history:
Received 23 February 2010
Accepted 31 July 2010

Keywords:
^{4}He-ions
^{7}Li-ions
CR-39
3D-track geometry
Track contours
Registration sensitivity
Angular dependence

ABSTRACT

Solid State Nuclear Track Detectors (SSNTD) irradiated in realistic radiation fields exhibits after chemical etching very complex track images resulting from different species of particles and their energy spectra and randomly distributed angles of incidence or emission. Reading out such an etched detector surface with a light microscope, quite different track opening contours are observed. Beside the number of tracks, typically their major and minor axes are measured. In this work following problems arising from such experimental situations will be investigated:

- the measurement of track contour parameters for oblique incident ^{4}He and ^{7}Li-ions of different energies and angles in CR-39 detectors
- the theoretical description of the angular variation of both axes.
- the possibility to extract physical and spectroscopic information from major and minor track axes.

This analysis is based on an intensive experimental program and the comprehensive study of theoretical models available for description of track revealing processes in CR-39.

1. Introduction

For more than 35 years the registration properties of Solid State Nuclear Track Detectors (SSNTD) are studied experimentally and theoretically. For simplicity and to obtain definite results, the detectors were irradiated with mono-energetic particles of a specific kind impinging perpendicular on the detector surface. Then the geometry of revealed tracks yields basic information on the physics of track formation. Vice versa, from such track images important particle spectroscopic information can be extracted.

Such studies have been performed for a very wide range of particle masses from protons to Uranium for incidence energies ranging from keV up to some hundreds of MeV per mass unit.

In practical applications, SSNTD irradiated under more realistic conditions show more complicated track images. Such typical applications are: environmental monitoring of Radon and its progenies, cosmic radiation monitoring for space flights, thermal and fast neutron spectroscopy, high energy physics, plasma diagnostics, high intense laser beam driven ion acceleration and others. In these cases complex track images will be produced by

- emission of particles of same type but different energy groups (Radon and its daughters) or spectra (recoil protons in fast neutron detection)
- emission of different secondary charged particle types from nuclear reactions inclusive recoil nuclei (fast neutron detection, plasma diagnostics and fragmentation processes in charged particle therapy)
- different incidence angles of emitted particles in forward direction (converter in thermal neutron detection, plasma diagnostics and laser driven ion accelerator)
- particle emission in backward direction against the etching front (cosmic ray, high energy particle physics and neutron registration in the detector bulk material)

In the past, a lot of experimental and theoretical investigations have been published to treat these problems in order to extract particle spectroscopic information and particle fluences from complex etched detector images. All experimental investigations have to be necessarily supported by theoretical calculations of the

* Corresponding author. Tel.: +49 351 6443045; fax: +49 351 463 37040.
E-mail address: hermsdf@rcs.urz.tu-dresden.de (D. Hermsdorf).

1350-4487/$ – see front matter
doi:10.1016/j.radmeas.2010.07.027

revealing process of tracks in three-dimensional geometry during the chemical etching. In the simplest case of perpendicular (with respect to the detector surface) particle incidence circular tracks appear after etching. From their 2-dimensional rotational symmetry in both planes (track opening contour at the surface and track profile in the detector depth) unique relations between the geometric parameters (diameter and track length) and physical parameters like particle species and its energy results. For oblique particle incidence the tracks are deformed to elliptical or more complicated egg- or drop-shaped contours and two different diameters, the major and minor axis D_{maj} and D_{min}, have to be differentiated, respectively.

Several approaches for the theoretical description of 3-dimensional track geometry have been proposed independently in the past. Somogyi and Szalay (1973), Fews and Henshaw (1982), Fromm (1990), Fromm et al. (1993) and Nikezic and Kostic (1997), Nikezic and Yu (2003a,b) proceed from different approaches of track revealing mechanism to solve the problem. The models of Fromm and Nikezic have been compared theoretically and experimentally by Dörschel for perpendicular and oblique particle incidence (Dörschel et al., 2003b and 2003a). Their equivalence could be verified by those studies. A comparison of all these models was carried out by Nikezic et al. (2006) and an overall agreement of results for calculated major axis for different incidence angles and energies of ^{4}He-ions was confirmed. Unfortunately, only a few experimental data were included in this analysis.

The basic quantity for all computing models is the track etch rate $v_T(x)$ along the particle trajectory which is dependent on the particle species and its actual energy $E'(x)$ at depth x in the detector material. This energy is reduced from initial energy E by ionisation losses. To compensate the dependence of track revealing from particle incidence energy and the etching conditions, commonly the etch rate ratio $V = v_T/v_B$ (also called registration sensitivity or track etch ratio) is used in the calculations in terms of $V(R')$ with the residual range $R' = R(E)$-x defined by the particle range R and the actual depth reached by the particle along its path into the detector bulk material. Therefore, the sensitivity function V is the crucial variable deciding about the reliability and accuracy of theoretical model predictions.

To simplify computations of track opening contours and track profiles Nikezic and Yu (2006) developed the code TRACK_TEST for calculating the formation of ^{4}He-ion tracks in all three dimensions. For ^{4}He-ions different V functions are available and these are included to be optionally chosen in application of the code. However, the assumption of a simple unique $V(R')$ function is invalid for particles heavier than ^{4}He-ions beginning with ^{7}Li-ions (Dörschel et al., 2002d). Then the sensitivity database has to be modified into a matrix in dependence on the incidence particle energy $V(E,R')$. Using such matrices the code SPUR has been created by Reichelt (2002) and first results for 3D-track opening and wall profile calculations were presented by Dörschel et al. (2003a,b) for particle masses ranging from protons to ^{12}C-ions.

The evaluation of detectors irradiated with complex particle fields is mainly performed by the observation of the detector's surface. Using light microscopes in transmission mode the brightness distribution of light inside the tracks can be helpful to determine spectroscopic information on the radiation field (Nikezic and Yu, 2009). Therefore, computer codes including the optical appearance of track openings on the surface of detectors have been developed. For automatic reading and evaluation of the surface of irradiated detectors the code TRIAC II (Patiris et al., 2007) can be applied whereas the code TRACK_VISION (Nikezic and Yu, 2008) explicitly can compute the brightness in the image of track openings.

The aim of this work is a state-of-art review and a critical check of

- the available experimental data of the angular dependence of major and minor track axes induced by ^{4}He-ions and ^{7}Li-ions in CR-39
- the possibility and reliability of the theoretical description or prediction of such data by available computer codes
- the influence of the different sensitivity functions V on the accuracy of calculations
- the possibility to extract the sensitivity V from major and minor track axes and its comparison with those obtained by other methods applied commonly

2. Experiments

2.1. Sample irradiation, etching and track axes measurements

In the frame of a comprehensive project a systematic series of experiments have been performed to measure the revealing of light ion induced tracks in full three-dimensional geometry, i.e. the track opening contour at the detector's surface and the track profile in the depth in variation on the particle energy and incidence angle. A small part of the huge amount of collected data has been published in the past concerning track profiles (Yamauchi et al., 2001; Dörschel et al., 2002a,b,c and 2003a,b) especially. Moreover, unpublished data based on experiments by Reichelt (2002) for ^{4}He and ^{7}Li-ions will be used and presented in this work.

As described in former publications, detector samples of dimensions 1 x 1 cm^2 and a thickness 1000 μm of pristine CR-39 TASTRAK were cut from large sized material delivered by TASL Ltd., UK. The samples were exposed to beams of ^{4}He and ^{7}Li-ions in vacuum. The irradiations were carried out with the low-flux irradiation facility of TU Dresden installed at the 5 MV tandem accelerator of the Research Centre Dresden-Rossendorf. The ion beam current was properly adjusted to limit the particle (or track) density on the sample's surface to the order of 20,000–50,000 per cm^2 at maximum in a reasonable irradiation time of few minutes. In this way overlapping tracks could be avoided for longer etching times and large elongations of the track contours. The angle of particle incidence was chosen to vary between 0° (or perpendicular incidence by definition in this work) and 87° to ensure the observation of tracks up to the critical angle θ_{crit}.

Finally, the detectors were etched by a standard procedure at 70 °C in a 7.25 mol l^{-1} NaOH solution described in a former paper too (Hermsdorf et al., 2007). The etching process was applied sequentially in time intervals of 6 h at maximum. During the etching treatment the concentration and purity of the etching solution were controlled regularly and refreshed after 6 h usage.

The track diameters have been measured with a NIKON optical microscope linked to the image processing software LUCIA provided by the NIKON Company too. The spatial resolution of this system is in the order of ±0.32 μm with a real pixel size of 0.16 μm at a magnification of 1100.

An example of track contours in dependence on the incidence angle is given in Fig. 1 showing tracks of 7.9 MeV ^{7}Li-ions etched for 6 h.

By the etching process a layer of thickness $h = x = v_B \cdot t$ is continuously removed which defines the actual surface of the detector at the depth x. Necessary, the bulk etch rate v_B has to be determined carefully. The fission fragment method was applied