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Proton induced target fragmentation studies on solid state nuclear track detectors using Carbon radiators

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ABSTRACT

One of the limiting factors of an astronaut's career is the dose received from space radiation. High energy protons, being the main components of the complex radiation field present on a spacecraft, give a significant contribution to the dose. To investigate the behavior of solid state nuclear track detectors (SSNTDs) if they are irradiated by such particles, SSNTD stacks containing carbon blocks were exposed to high energy proton beams (70, 100, 150 and 230 MeV) at the Proteus cyclotron, IFJ PAN -Krakow. The incident protons cannot be detected directly; however, tracks of secondary particles, recoils and fragments of the constituent atoms of the detector material and of the carbon radiator are formed. It was found that as the proton energy increases, the number of tracks induced in the PADC material by secondary particles decreases. From the measured geometrical parameters of the tracks the linear energy transfer (LET) spectrum and the dosimetric quantities were determined, applying appropriate calibration. In the LET spectra the LET range of the most important secondary particles could be identified and their abundance showed differences in the spectra if the detectors were short or long etched. The LET spectra obtained on the SSNTDs irradiated by protons were compared to LET spectra of detectors flown on the International Space Station (ISS): they were quite similar, resulting in a quality factor difference of only 5%. Thermoluminescent detectors (TLDs) were applied in each case to measure the dose from primary protons and other lower LET particles present in space. Comparing and analyzing the results of the TLD and SSNTD measurements, it was obtained that proton induced target fragments contributed to the total absorbed dose in 3.2% and to the dose equivalent in 14.2% in this particular space experiment.

1. Introduction

Spacecrafts revolving in Low Earth Orbit (LEO) meet a very complex radiation field. Usually the primary ionizing radiation is described as having three main sources: (i) galactic cosmic rays (GCRs), which are atomic nuclei and originate outside the solar system; (ii) solar particle events (SPEs), which are charged particles emitted by the sun and (iii) trapped particles (protons and electrons) in the Earth's radiation belts [1]. Protons compose 85% of GCRs, 99% of SPEs and they are present in the Van Allen Belts trapped by the geomagnetic field [2]: these are the main components of the complicated radiation field in space. Trapped protons have energies from several to several hundred MeV with a broad peak between 150 and 250 MeV. The International Space Station (ISS) and other spacecrafts, flying in LEO, cross the trapped proton belt in the South Atlantic Anomaly (SAA) region.

SSNTDs have been used onboard the ISS and satellites in numerous experiments, see [3,4], therefore it is important to become acquainted with their response to protons as much as possible. The Linear Energy Transfer (LET) values of high energy protons are lower than the detection threshold of the SSNTD material applied in these missions; they can be detected through the secondary particles, which are formed when the constituent atoms of the detector participate in fragmentation processes. Although investigations of the target fragmentation processes at high proton energies using etched track detectors has been actively investigated by numerous researchers (e.g. [5–7].), we can still obtain new data from fragment measurements to improve our knowledge in the field of space dosimetry with these detectors.

During irradiation latent tracks are induced in the detector material. They can be developed by etching the detectors in alkali solution. In this procedure a definite layer is removed from the surface of the material; in the meantime the tracks are enlarged to become visible by optical microscope. If the path of the particle ends within the etched off layer, the latent track will disappear and the particle will not be detected or its track will become overetched. For such reasons, it is important to

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Table 1
The most frequently occurring fragmentation products of Carbon. Subscript *pf* refers to the primary fragment.
Source: The data were compiled by J.K. Pálfalvi, published in [9].

Primary fragment	Coupled particles	Cross section (mb)	$Energy_{pf}$ (MeV)
^{6}Li	^{7}Be	9.8	~5
^{7}Li	^{4}He + 2 p	7.8	~6
^{7}Be	$^{4}He + ^{2}H$	12.2	~7
^{9}Be	^{3}He + p	2.5	~9
^{10}Be	3 p	1.8	~6
^{10}B	^{3}He	19	~6
^{11}B	2 p	63	~6

optimize the etching procedure. The geometrical parameters, usually the major and minor axes of the tracks seen on the surface of the detector as little ellipses, are measured by an image analyzer. These parameters are used then to calculate the track etch rate ratio, which is converted to LET applying adequate calibration functions [8]. Finally the LET spectra are constructed, from which the dosimetric quantities (absorbed dose and dose equivalent) are determined.

If a proton collides with the nuclei of the detector material (made of polyallyl-diglycol-carbonate or PADC: $C_{12}H_{18}O_7$), depending on its kinetic energy, various types of nuclear interactions can occur. Considering the fragmentation processes, (p → ^{12}C) is the most abundant, succeeded by the (p→ ^{16}O) interaction and resulting in similar fragments. Table 1 presents some of the most important fragmentation products of the ^{12}C target induced by high energy protons [9]: these are ions from H up to C (^{1}H, ^{2}H, ^{3}He, ^{4}He, Li, Be, B, C).

The energy of the particles with $Z > 2$ is usually lower than 10 MeV. He ions may have higher energies, up to ~20 MeV. The energy of the secondary protons may be even higher and they may leave the detector without considerable energy deposition, since their LET may be less than 10 keV μm^{-1}, which is the detection threshold of the PADC material used in the experiments [10]. Fig. 1 presents the ranges in this material of the ions mentioned above, calculated by the SRIM2013 code [11]. In the standard method for the evaluation of space detectors this group applies two steps of etching in 6 N NaOH solution at 70 °C, the first lasts for 6 h and the second for 15 h. In this way an 8 μm and a 20.1 μm thick layer is removed from the surface, thus it is expected that the majority of the tracks visible after both etching steps will be caused by He ions (on a detector irradiated by high energy protons). Tracks of ions with $Z > 2$ will be present in higher number after 6 h etching, as many of them will be etched off the surface after 15 h etching due to their short range.

2. Experimental setup

SSNTD stacks were irradiated in March 2016, at the proton accelerator in Krakow (IBA Proteus C-235 cyclotron of the Institute of Nuclear Physics, Polish Academy of Sciences - IFJ PAN) with nominal energies of 70, 100, 150 and 230 MeV. The proton fluence was 1E+8 cm^{-2} in each case.

The proton fluence was determined (calculated) from the measured dose values for particular energies used for irradiation. The doses were measured using a parallel plate ionization chamber and reference class electrometer. During irradiation the detectors stack was located at the isocentre of facility in the beam axis and irradiated perpendicularly to the surface of stack. The dose was verified in each case by thermoluminescent detectors (TLDs of type ^{7}LiF:Mg, Ti; manufactured at IFJ PAN) exposed simultaneously with track detectors. The doses measured by TLDs were practically the same as measured by the ionization chamber.

The stacks contained from top to bottom 2 sheets of 1 mm thick SSNTDs, a 2 mm thick carbon block in the middle and 1 sheet of SSNTD (Fig. 2). The carbon block was included to study the carbon fragments separately, as their role is highly important in the case of living tissues. The LET values of the incident protons were below 1

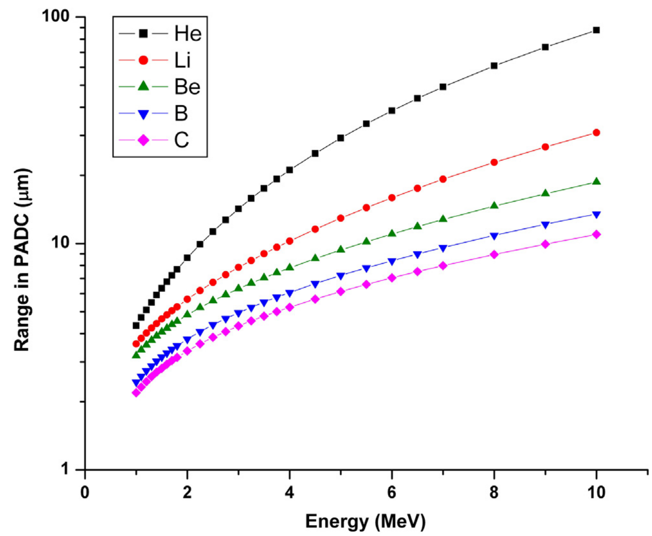

Fig. 1. Ranges of the most important secondary particles induced by protons on the ^{12}C nucleus.

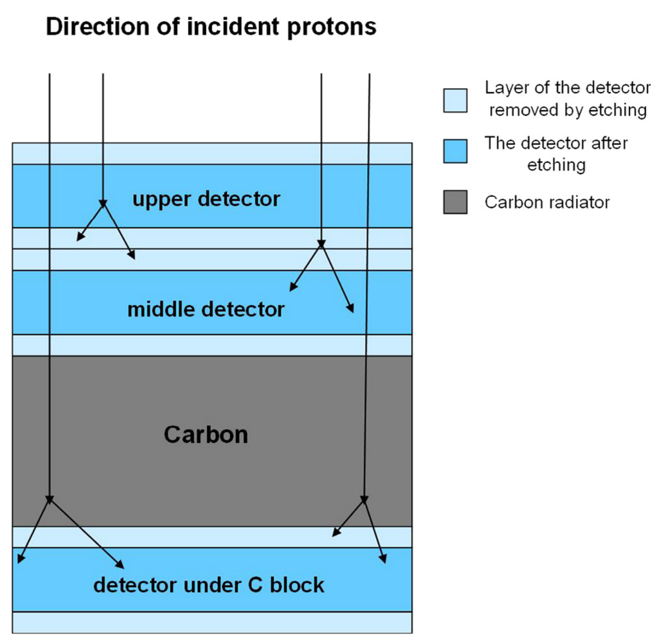

Fig. 2. Composition of the PADC stacks irradiated by high energy protons: target fragments are formed inside the material of the detector sheets and also inside the Carbon blocks. If the range is low, the tracks disappear after etching. The incident protons with high energy and low LET cannot produce tracks. The dimensions are not to scale.

keV μm^{-1}, lower than the detection threshold of the detector (~10 keV μm^{-1}), which means that after etching no primary particles can be observed on the surface. However, secondary particles (recoils and fragments) are generated. It was expected that the highest number of fragments would be found on the detector positioned under the carbon block.

3. Track measurements

The measurements of the detectors showed good agreement with the expectations. Fig. 3 presents the track densities on each detector inside the stacks after 6 h etching: the highest number of tracks can be observed under the carbon block. As the proton energy increases, the number of