Nuclear Track Detectors for Charged Particles and Neutrons

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1 INTRODUCTION

It was with great emotion that I accepted to be a guest speaker to this memorial section dedicated to my old-time friend, Prof. Radomir Ilić. In addition to being one of the most outstanding scientists in the field of nuclear tracks, Prof. Radomir Ilić has been always highly acclaimed by the scientific community for his enthusiasm, his warm friendship, and his great vitality.

Through his successful editorial activities [1-7], Prof. Ilić has proved to be very able to address the field of nuclear tracks to very wide audiences with special regards to young students. It was here in Portorož, that Prof. Radomir Ilić was our host as the organiser of the 21st International Conference on Nuclear Tracks in Solids [4]. All the participants have great memories of this very successful international conference. For all these reasons, the 2006 edition of the International Conference on Nuclear Energy for New Europe, with its wide audience and its venue at Portorož, can be considered as one of the most appropriate forum for the memorial lecture of Prof. Radomir Ilić. The present paper will be dealing with the solid state nuclear track detectors-SSNTDs and their successful applications for the measurements of cosmic-ray-neutrons and terrestrial radioactivity, namely radon.

2 CONVENTIONAL DETECTORS AND DAMAGE TRACK REGISTRATION

The response of conventional detectors like gas counters, scintillators, semiconductors, nuclear emulsions, thermoluminescent materials, etc., results from radiation-induced energy deposition in sensitive volumes of macroscopic amount of matter. These detectors are adequate for the dosimetry of sparsely ionizing radiations (X- and γ-rays), which loose energy by fairly random distribution of energy deposition. By contrast, heavily charged particles, and/or neutron-induce particles interact with matter by depositing high concentrations of ionization energy in microscopic and ultramicroscopic volumes surrounding the tracks, which properties determine the high biological effectiveness of these radiations.

In particular, to provide guidelines for the development of suitable detectors for neutron dosimetry, it is necessary to analyse the differences in the spatial distributions of energy deposition between neutron and γ-interactions with tissue [8].

Particular emphasis has been given to these differences in the field of microdosimetry, where an extensive analysis has been made on the local energy depositions both at the cellular and subcellular levels [9].

The comparison between neutron and γ-ray interactions with tissue is illustrated in the diagrams of the upper part of Figure 1 [8]. These diagrams show two monolayers of biological cells (with diameter of about 5 μm) which received a dose of 1 mSv/y of gamma exposure (as typically received from natural terrestrial radiations) and 1 mSv/y of neutrons (as it occurs on high altitudes mountains such as Cervino-Italy [10].
Figure 1: Upper part: Monolayers of biological cells irradiated respectively to gamma rays (left side) and fast neutrons (right side). Lower part: Single proton track in tissue.

The differences appear very clear since, in the case of gamma rays, there is one radiation interaction for every cell in one year, while for neutron irradiation only one out of 2000 cells is crossed by a track which deposits a dose which is about 500 times higher than that due to gammas. The first detector capable of measuring energy depositions in a microscopic element of matter (typically biological tissue) is the Rossi counter [11]. In fact, this counter has the characteristics that it can simulate a microsphere of biological tissue.

Advanced portable types of Rossi counters have been developed (known as the tissue equivalent proportional counter-TEPC) which are successfully used for radioprotection dosimetry in mixed field of radiations [12], such as gamma-neutrons and/or cosmic rays.

In order to understand the mechanisms of track formation and etchability, it is necessary to refer to the spatial distribution of energy depositions at submicroscopic distances from charged-particle trajectories. The lower part of figure 1 shows a magnified view of a single neutron recoil track (typically 1 MeV proton track in tissue), together with important biological targets like DNA and the cell membrane. This track structure is formed by a track core (characterised by high energy deposition) and delta rays which deliver energy at a distance from the track core. For example, a dose of the order of 1MGy is deposited at 10 Å radial distance from 1 MeV proton track in tissue [13]. At such submicroscopic distances from nuclear tracks, the difference between sparse radiation (X- and γ-rays) and high-LET particles are enormous. It is the high energy deposition in the vicinity of the particle trajectory the most crucial quantity for the registration of damage tracks[14]. In fact, the most important characteristic of damage track detectors is that there is a minimum density of damage along the core of the track that will permit the track to be enlarged by etching. The existence of this threshold is one of the most valuable characteristics of damage track detectors, which explains their ability to discriminate against large fluxes of lighter energetic particles, electrons, gamma rays, etc.
By contrast, the responses of detectors with macroscopic and microscopic volumes are sensitive to the whole energy loss along the track. In situations where the saturation phenomena in the vicinity of the track are predominant, such as with organic scintillators, the response to the outer part of the track is relatively much larger than to the core. For these reasons, the scintillators can be considered to be just the converse of the damage track detectors [15].

3 ETCH TRACK GEOMETRY

A track becomes etchable when the rate of etching along the track, \( V_t \), exceeds the rate at which the surface is etched, \( V_b \) [16]. If the track is not perpendicular to the surface, then the component of \( V_t \) perpendicular to the surface must exceed \( V_b \) for registration to occur. Figure 2 (a) shows tracks of neutron-induced fission fragments entering a polycarbonate detector from a fissile radiator, while Figure 2(b) presents tracks of recoil-particles induced by neutrons in the detector itself. Since for fission fragments \( V_t \) is much larger than \( V_b \), the tracks are elongated and well defined. Short etch pits instead of fully developed tracks appear in Figure 2(b), since in this case \( V_t \) is not much larger than \( V_b \).

![Etched tracks of fission fragments (a) and neutron-recoils (b)](image)

Figure 2: Etched tracks of fission fragments (a) and neutron-recoils (b)

For most applications of damage track detectors in dosimetry, it is necessary to evaluate low track densities (1 to 1000 tracks per cm\(^2\)) for large number of detector foils, which may have areas up to 100cm\(^2\)). The shortcoming of counting individual tracks in large detector areas under the microscope have been overcome through the development of the spark counter and of different image analyzer systems for the automatic counting of both chemically and electrochemically etched tracks [16]. These developments have greatly...
facilitated the applications of track detectors in the measurement of cosmic ray neutrons, in personal neutron dosimetry and in large scale survey of radon in dwellings [7, 16-17].

4 COMIC RAY MEASUREMENT BY DAMAGE TRACK DETECTORS

Passive detectors are very attractive for cosmic ray measurements both at aircraft and space altitudes, because of their small size, low weight, lack of need of electrical power and of the stringent requirements for the environmental parameters (temperature, vibration and interference with the on-board instrumentation). Different passive multidetector stacks have been developed for in-flight measurements which make it possible to measure low- and high-energy neutrons, and HZE particles [10, 17-18].

The stack consists of several types of passive detectors for the registration of recoil- and fission-fragment-tracks induced by neutrons. Most of these detectors have been used on earth for the assessment of the occupational exposure [14], or in outer space for cosmic-ray physics and/or for the assessment of the dose received by astronauts [16-17, 19-20].

A great deal of efforts and new developments have been required to make these detectors useful for in-flight measurements [17, 21] with special regard to the use of large area stacks. Even though these multidetector systems present the complexity typical of cosmic ray stacks, the scanning of many different types of detectors is relatively simple and rapid, as required for dosimetric applications. In particular, a simple microfiche reader can be useful to scan large areas of different types of neutron detectors for the counting of both fission-induced aluminum spots in spark-counted replicas or electrochemically etched recoil tracks [17].

A major drawback of damage-track detectors is their large and unpredictable background. This problem has been finally solved by using the detection principle of counting coincidence-track events on matched-pair of detectors, not only for long-range particles but also for very short tracks such as those induced by neutron recoils [17] which, once etched electrochemically, can be easily seen on the screen of a microfiche reader.

5 STACK FOR NEUTRON SPECTROMETRY

The basic requirements for a stack for neutron spectrometry (based on the unfolding procedures) is to have different detectors, which have a known response as a function of the neutron energy and chosen in such a way that all the parts of the expected energy range are included. In order to cover both the low- and the high-energy range of neutrons, two categories of detectors have been chosen which are based respectively on the registration of neutron-induced recoil-tracks in organic materials and neutron-induced fission fragments in heavy elements [17].

Neutron induced fission cross-sections for some heavy nuclei ($^{235}$U, $^{238}$U, $^{232}$Th, $^{209}$Bi) are internationally recommended as secondary standards for neutron flux monitoring in the energy region above 20 MeV[17].

In particular, heavy nuclei such as bismuth, gold and tantalum have been studied for the detection of high energy neutrons through fission-induced reactions[17]. In spite of the low fission cross-sections of these materials, sufficiently high sensitivity can be achieved by using a multi-detector stack. These achievements are important, since these detectors make it possible to exploit the excellent characteristics of the fission reactions in bismuth, gold and tantalum for the measurements of high energy neutrons, such as:

- excitation functions well above 20 MeV which eliminate the influences of low energy neutrons,
- smooth variation of the cross-section with neutron energy,
- mono-isotopic and non-radioactive materials, which make them easy to transport and handle.

Figure 3 shows the fission-cross section of bismuth, gold, tantalum and thorium respectively [17].

![Figure 3: The neutron fission cross-section, (\(\sigma(n,f)\)), of \(^{232}\)Th, \(^{209}\)Bi, \(^{197}\)Au and \(^{181}\)Ta versus the neutron energy. The right hand ordinate is scaled for the thorium cross-section (13).](image)

The upper curve of Figure 4 shows the neutron spectrum obtained with a passive stack of track detectors flown in the cockpit of an MD-11 aircraft along the route Milan-Los Angeles for a total of 670 hours from November 1993 to May 1994 [22]. The lower spectrum has been obtained by exposing the stack during the same period at 3500 m mountain altitude[23-24]. Both spectra start at 100 keV. The registration of neutrons with energy lower than 100 keV has been avoided for practical reasons. This approach is justified since the contribution to the dose by neutrons with energy below than 100 keV is negligible [22].

6 NEUTRON AND RADON DOSIMETRY: A PARALLEL HISTORY

Since their discovery, damage track detectors have been extensively investigated for the solution of the complex problem of personal neutron dosimetry [14]. In the late 60’s and 70’s, several laboratories from throughout the world have developed new neutron dosemeters based on damage track detectors [16, 25-32].

Most of the scientists actively engaged in the 70s in the solution of the complex problem of personal neutron dosimetry have extended their interests in the field of radon in order to develop individual monitoring for exposure to radon decay products in mines by using the same SSNTDs [16, 25-32].
Figure 4: Upper curve: Neutron spectrum at aircraft altitude (Milan-Los Angeles)
Lower curve: Neutron spectrum at mountain altitude (Matterhorn, Italy)
Note lower graph is plotted with a linear ordinate.

Prof. Radomir Ilić himself carried out parallel research activities in neutron and radon dosimetry [7,34]. The personal dosimetry of neutrons and that of radon decay products have had a parallel history and a lot of common traits, such as the same track detectors, the same etching and counting procedures, the same scientists and/or laboratories involved. Despite the fact that the dose to neutrons is due to external exposure while that to radon decay products to internal exposure, identical monitoring strategies have been often adopted, within which a given track density is converted into a neutron dose or otherwise into a dose of radon decay products by appropriate conversion coefficients. In the case of radon decay products, this approach has been facilitated by measuring the radon gas concentration (as surrogate), which can be converted into the radon decay product concentration if the equilibrium factor is either monitored or known to have a given value [33].

A personal dosimeter for miners for radon-only gas, known as radon film badge was first proposed by Geiger in 1967 [35]. It consisted of a chamber into which radon was allowed to diffuse enclosing a nuclear track emulsion to detect the alpha particles emitted. These nuclear emulsions were then used typically for personal neutron dosimetry. They were unsatisfactory both for neutron and radon dosimetry, since their response was affected by humidity, temperature, light, etc.

Once the alpha-sensitive plastics have become available, they have soon resulted very attractive for both types of dosimetry.

7 PASSIVE RADON MONITORS

Passive radon monitoring based on diffusion chambers enclosing alpha-sensitive plastics have been increasingly successful both for uranium miner-dosimetry and elsewhere,
because of their simplicity, robustness, and ease of automation of track counting [33]. In the 70’s, passive radon-only gas detectors have been also developed for completely different applications in mind than those for personal dosimetry, such as in uranium prospecting and earth sciences[7, 35-38]. For more than one decade, polycarbonate and cellulose nitrate detectors were the most common plastic detectors for both neutron and radon dosimetry. It was only in 1978 that the poly-allyl diglycol carbonate-PADC detector (known with its trade name CR-39: Columbia resin 1939) was first introduced as track detector [39]. With this new material it was finally possible to detect alpha particles with any energy in practice [16, 39]. Just prior to the discovery of CR-39 detector, Frank and Benton [40] have described the basic methods for the detection of radon and its decay products. These methods have remained unchanged and most of the improvements are essentially due to the use of CR-39 detectors. In particular, these detectors have resulted the most convenient for closed-type radon monitors, since their high sensitivity makes it possible to obtain compact passive detector devices. For example, by using CR-39 detectors, a new personal radon dosimeter has been developed at the National Radiological Protection Board-NRPB with such small size of the diffusion chamber that the entire device is compact as any other personal dosimeter for x, γ, and n radiation [41], as shown in Figure 5, where it can be seen that even the shapes of neutron and radon dosimeters may be identical.

![Figure 5: Different shapes of personal neutron and radon dosemeters](image)

Most of the radon monitors, initially developed for completely different applications in mind, have been eventually used for large scale survey of indoor radon.

With the current implementation within Europe of the European Union Directive 96/29, [42] applications of damage track detectors is increasing drastically, specially for the assessment of the exposure of the workers to natural sources of radiation. In this case, the
early work on personal neutron/radon dosimetry, is highly valuable to tackle these new
problems of occupational monitoring.

REFERENCES


[31] L. Tommasino Method and apparatus for electrochemical development of damage tracks produced by radiation on insulating materials. Italian Patent N° 51929/70


