COMPUTER SIMULATION OF THE PROCESSES IN A PAIR OF CR-39 TRACK DETECTORS DURING NEUTRON EXPOSURE

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ABSTRACT

A simple computer simulation was developed of the fast neutron response of a detector composed of two foils of CR-39 solid state track detector and used for measurement of low neutron fluxes. Some standard program packages were used for the simulation. The energetic and spatial distribution of the recoil nuclei formed in the material CR-39 during neutron irradiation was calculated with the MCNP program package. On the basis of this distribution a Monte Carlo procedure was run and latent tracks in the CR-39 detectors produced by the recoil nuclei were generated. Additionally a calculation procedure for the chemical track etching was performed to obtain the detector response. The simulation was performed for various incident neutron energies and chemical etching parameters. A comparison of the calculated results with the experimental obtained data is given.

1 INTRODUCTION

In some materials, mainly polymers, minerals and glasses, the radiation damage made by ions in their passage through the material, can be made visible by chemical etching. These materials are used as Solid State Nuclear Track Detectors (SSNTD). They are usually formed in the shape of lamellas of thickness of 0.5 to 1 mm, or thin foils of thickness from 3 to 50 µm. The most sensitive material used as an SSNTD is allyldiglycol carbonate (CR-39). It can be used for the detection of all ions and protons from energies of 100 keV upwards.

After the irradiation track detectors are, as mentioned, etched in a caustic solution to enlarge the latent ion tracks and these become visible under an optical microscope. The size and shape of these pits are dependent on the rate, at which the detector material is removed during chemical etching at damage sites and at undamaged regions [1]. The subsequent
counting of tracks under an automatic microscope system is the standard procedure for the evaluation of such detectors after chemical etching.

CR-39 detector with the chemical formula $\text{C}_{12}\text{H}_{18}\text{O}_6$ is of particular interest for the development of a fast neutron dosimeter [2]. Among several advantages, the most important feature of this detector is its high sensitivity to protons. Fast neutrons interact with the constituents of the CR-39 detector and produce $\text{H}$, $\text{C}$ and $\text{O}$ recoils.

The major drawbacks of etched track detectors in the assessment of low neutron doses are their limited sensitivity and unpredictable background [3]. The later arises from impurities in the detector and tracks which do not originate from neutron induced events. The background problem can be solved by a new registration method based on counting coincidence spots on a geometrically matched pair of detectors [4]. The essence of the coincidence counting method is the measurement of tracks with a pair of SSNTD foils in close contact. In this way, some recoil nuclei produced close enough to the exit surface of the first detector leave two tracks, one on each of the evaluated surfaces that were in contact during neutron irradiation (Fig. 1). After counting, only the tracks found on the same spot on both surfaces produced by the same nuclei are taken into account. These tracks are called coincidence tracks. Since the probability of track-similar defects being on both detectors at the same spot is small, they can be to a large extent excluded from the signal. With the same detector configuration neutrons can be detected in the standard way, namely by deriving the fluence from the measured track density on a single detector foil.

An extensive experimental programme is needed to determine the response of the detector at different neutron energies. Therefore, a theoretical method to evaluate the response of the detector would be of great help. The calculated results can then be verified experimentally or compared with published data. The aim of the present work was the calculation of the response for the described coincidence detector. In order to gain insight into the processes contributing to track production during neutron irradiation and into likely effects of changing the etched layer, we developed a computer simulation partly based on the Monte Carlo technique using a simplified model. A tested pseudo random number generator Ran2() [5] was used. The recoil nuclei distribution was calculated with the help of the MCNP program package.

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**Figure 1**: The coincidence detector set-up: two foils of CR-39 material in contact with marked recoil nuclei damage tracks. In the chemical etching procedure the surface layers of the detectors are removed and the tracks are enlarged. After automatic counting of the tracks on surfaces, marked with $A'$ and $B'$, only tracks found at the same spot on both surfaces are taken into account - consequently only track pairs produced by the same nuclei.
2 SIMULATION PROCEDURE

2.1 Theoretical considerations

In most of the previous theoretical work concerning the detector response of CR-39 to fast neutrons only the contribution due to recoil protons was taken into account [6]. The contributions due to the C and O recoils and other charged particles were neglected. In order to mimic the actual situation, we paid attention to all recoil reactions, but neglected \((n, \alpha)\), \((n, p)\) and \((n, d)\) reactions. However, in the energy range below 6 MeV the contribution of the last three reactions was found to be negligibly small [7]. On account of this, the simulation results can be relied on for fast neutrons with energies lower than this value. It should also be mentioned that the angular dependent response of the detector was not studied.

For the input of the simulation procedure the spectral distribution of the incident neutrons and the etched layer removed from the detector foils were needed. As output the number of tracks on both detector foils, the number of coincidence tracks and their distribution by size were given. The procedure consisted of stages, as follows.

2.2 Simulation procedure algorithm

The required energy and angular distribution of the recoil nuclei was calculated indirectly through the distribution of scattered neutrons, which can be easily determined with the help of the MCNP program package (the version MCNP 4C was used). More precisely: for an arbitrary energy distribution of incident neutrons the distribution due to energy and direction of the neutrons after the passage through a foil of CR-39 material was calculated. Using the acquired data the Monte Carlo procedure could be applied. In accordance with the distribution obtained the neutron scattering events in the detector material were generated. It was found that the share of fast neutrons that are scattered more than once in a detector foil of thickness 0.7 mm (the thickness of the foil in the modelled detector) is less than 1% [8]. Thus without loss of accuracy, multiple scattering of neutrons was neglected.

The next step was the calculation of the energy and direction of the recoil nuclei. This was done on the assumption of elastic scattering, which is a good approximation for neutrons of energies lower than 6 MeV [8]. The standard equation for elastic scattering was used [9]. The result can be trusted only in the approximation that the nuclei are at rest before scattering and that their binding energy is small enough. Both assumptions are fulfilled for incident neutrons with energies higher than 100 keV [10].

For every generated recoil nucleus the corresponding length of the latent track in the detector was calculated with the program SRIM [11]. Knowing the co-ordinates of the beginning and endpoints of the latent track, the size of the track opening and other parameters (radius of the track tip, track depth) of the visible track after the etching procedure could be calculated. A procedure using tabulated values for the etching rates of CR-39 [12] was used for this purpose.

For every generated recoil nucleus the main parameters of the corresponding etched tracks on the surfaces A’ and B’ marked on Figure 1 were calculated. These parameters are the major and minor axes of the track opening, the depth of the track and the radius of the track tip. Not all of the recoil nuclei pass the boundary between the two detector foils. In this case etched tracks are formed at most on one of the surfaces (A’ or B’).
2.3 Etched track registration criteria

The criteria used for deciding whether a recoil nucleus track should be registered were based on the properties of the TRACOS automatic counting system [13] used in our laboratory, and may be summarised as follows:

(a) the major axis of the elliptically shaped track opening must be larger than 1 \( \mu \)m,
(b) the ratio between the track tip radius and the minor axis of the track must be smaller than 0.7. This was established empirically by observing tracks from protons of known energies, originating from an accelerator.

It should be noted that the criteria for deciding whether a track should be registered or not, due to their simplicity, are the largest possible sources of error. This refers more to criterion (b) especially for O and C recoil nuclei tracks whose detection efficiency can be slightly higher, since the reference observations were performed for protons only. In the prosecution of this work other methods should be tested; for example the more precise track shape calculation method with the calculation of the optical properties of the track under a microscope [14].

2.4 Goals of the simulation

The simulation was performed to acquire the following data:

1. The response of the coincidence detector. This is given as the number of detectable tracks per incident neutron.
2. The best value for the thickness of the detector layer \( h \) removed during chemical etching.
3. The ratio between the number of the coincidence tracks and between the number of tracks found on each single detector.
4. The ratio of the tracks originating from the recoil nuclei of each element.

3 RESULTS

The detection efficiency of a pair of CR-39 detectors was calculated by running the code for \( 10^7 \) histories for different neutron energies and etching parameters. As a result, the total number of detectable tracks on each of the detectors and the number of the coincidence tracks was determined.

Fig. 2 shows the three types of calculated response for the coincidence detector as a function of the neutron energy. The etched detector layer was 9 \( \mu \)m. The detection efficiency on each single detector foil decreases with increase in neutron energy. The higher value of the efficiency for low neutron energies is the consequence of the higher elastic scattering cross-sections for H, C and O in this energy range. The coincidence response, however, increases with increasing neutron energy in the lower energy region. It reaches its maximum at approximately 1 MeV and starts to decrease as the neutron energy further increases. This can be explained as follows. The latent tracks left in the material by low recoil nuclei energies corresponding to lower neutron energies are short. The correlation between etched tracks on both surfaces is small. The reason for the efficiency decrease for faster neutrons is the same as described above for a single detector foil.
Figure 2: Response for each of the detector foils and the coincidence response as a function of the incident neutron energy. The thickness of the etched layer is 9 µm.

The partial contributions towards the coincidence response from interactions with each constituent of the CR-39 material are shown in Fig. 3.

Figure 3: Energy dependence of the coincidence response for hydrogen, carbon and oxygen nuclei at different values of the etched layer $h$.

Fig. 3 shows that the share of the tracks originating from the O and C recoil nuclei is negligible for neutron energies lower than 1 MeV but is an important contribution to the overall response for neutron energies of a few MeV. The reason for this behaviour is as follows. In the elastic scattering reaction only a small portion of the neutron energy is
transferred to the heavier nuclei. In addition their ranges in CR-39 are shorter than the range for protons of the same energy and correspondingly the correlation between tracks on the two detector foils is very weak. The same is valid for the number of coincidence tracks. The reason for the increasing response in the higher neutron energy region is the higher etch track detection efficiency of the heavier nuclei and the higher track correlation due to longer tracks, despite their smaller scattering probability.

An estimation of the accuracy of the calculation was performed by comparison of the results with experimentally obtained ones. The experiments were performed in the exposure room of the TRIGA Mark II reactor of the J. Stefan Institute in Ljubljana and these results are summarised in [8]. The energies of the neutrons, at the place of the irradiation, were mainly lower than 1 MeV. The neutron spectrum is presented in detail by Krištof [15]. This spectrum was described discretely for the purpose of the simulation. The calculated response of the detector is shown in Fig. 4.

The detector layer etched in the experiments was 9 µm. The experimentally obtained results for the response on both detector surfaces and the coincidence response deviated by no more than 30% from the ones obtained theoretically. The values of the etched layer and the neutron spectrum used in the calculation, were adjusted to the experiment. The deviation probably originates from the simplified criteria used for track recognition, as already mentioned.

![Response of each single detector foil and the coincidence response for an incident neutron spectrum that was used for the experiments.](image)

**Figure 4:** Response of each single detector foil and the coincidence response for an incident neutron spectrum that was used for the experiments.

## 4 CONCLUSIONS

A Monte Carlo based computer simulation was developed for the calculation of the response of a specific fast neutron detector, composed of two CR-39 foils. The calculation can be performed for different incident neutron spectra and different thickness of the etched layer. The contributions from the H, C and O recoil nuclei can be calculated separately. As the output the distribution of the tracks according to their sizes and other parameters can also be obtained. In spite of the simplicity of the simulation, the calculated results agree well with the experimentally obtained ones.
REFERENCES


