REVIEW OF SCIENTIFIC INSTRUMENTS **85**, 022102 (2014)

Computer program for the sensitivity calculation of a CR-39 detector in a diffusion chamber for radon measurements

D. Nikezic,[1,a)] K. N. Yu,[2] and J. M. Stajic[1]
[1] *Faculty of Science, University of Kragujevac, R. Domanovica 12, Kragujevac 34000, Serbia*
[2] *Department of Physics and Materials Science, City University of Hong Kong, 83 Tat Chee Avenue, Hong Kong*

(Received 19 July 2013; accepted 10 October 2013; published online 14 February 2014)

Computer software for calculation of the sensitivity of a CR-39 detector closed in a diffusion chamber to radon is described in this work. The software consists of two programs, both written in the standard Fortran 90 programming language. The physical background and a numerical example are given. Presented software is intended for numerous researches in radon measurement community. Previously published computer programs TRACK_TEST.F90 and TRACK_VISION.F90 [D. Nikezic and K. N. Yu, Comput. Phys. Commun. **174**, 160 (2006); **178**, 591 (2008)] are used here as subroutines to calculate the track parameters and to determine whether the track is visible or not, based on the incident angle, impact energy, etching conditions, gray level, and visibility criterion. The results obtained by the software, using five different V functions, were compared with the experimental data found in the literature. Application of two functions in this software reproduced experimental data very well, while other three gave lower sensitivity than experiment. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4865157]

I. INTRODUCTION

Long term, passive measurements of radon (^{222}Rn) concentrations in air are performed with solid state nuclear track detectors (SSNTD) that are sensitive to alpha particles emitted by radon and its short lived progeny. Detectors are usually located within a cup that is closed with some permeable substance, like filter paper, which allows radon diffusion and prevents penetration of radon progeny, dust, and humidity into the chamber. Such devices are usually called a "diffusion chamber," "cup," or "radon dosimeter."[3–5] A survey of various designs and combinations of SSNTD with other media (electrets, active charcoal, etc.) used for radon measurements was given in Nikolaev and Ilic.[6] More recent developments in the construction of radon dosimeters have been described by Nikezic and Yu.[7]

The track density on a detector, N [track/m^2], which is a measurable quantity, is related to the average radon concentration C_0 [Bq/m^3] during the irradiation time t [s], through the sensitivity, k [m], as follows:

$$N = kC_0t. \quad (1)$$

Sensitivity is determined experimentally or theoretically. It is defined as track density (in track/m^2) per unit exposure (Bqs/m^3). Traditionally, sensitivity is given in track/cm^2 per Bqd/m^3 (to be divided by 8.64 to convert to m) or in track/m^2 per Bqh/m^3 (divided by 3600 to convert to m). Experimental conditions during calibration and measurements should be the same, or, if this is not possible, as similar as possible. Any changes in the experimental setup, exposure, etching, or readout procedure request additional calibration and determination of a new calibration factor.

Several authors have presented various calculation methods for sensitivity determination. An analytical method and analysis of all possible cases of geometrical relationships between the effective volume and chamber walls were reported in Askari *et al.*[8] Unfortunately, problems analyzed by Askari *et al.*[8] were limited to a point like detector located in the centre of the bottom of a cylindrical diffusion chamber, while in reality the detector has real physical dimensions. Other authors presented Monte Carlo calculations of the calibration coefficient.[9–19] The Monte Carlo approach is more convenient than the analytical one when real physical dimensions of the detector are considered. Monte Carlo simulation also enables determination of radial track density distribution on detector in the bottom of a diffusion chamber.

Although a lot of effort was devoted to the development of models and calculation of sensitivity, there is no widely available computer software for this purpose. The objective of this work is to provide computer software for calculation of the sensitivity of a CR-39 detector in a diffusion chamber for radon measurements. The program operates for a conical and cylindrical diffusion chambers, assuming that a circular detector is located in the bottom of the chamber. The presented computer software may be used for optimization of the diffusion chamber, detector dimension and shape, and the complete measurement procedure.

II. DESCRIPTION OF COMPUTER PROGRAMS AND INPUT PARAMETERS

The software consists of two programs written in the standard Fortran 90 programming language. The algorithms and codes are relatively simple and may be easily translated into other computer languages. Executable versions are provided and may be downloaded from the following web

[a)] Author to whom correspondence should be addressed. Electronic mail: nikezic@kg.ac.rs

address: http://www.pmf.kg.ac.rs/radijacionafizika/Sensitivity.html.

A. Program QUEST.F90

The first program that should be executed is called QUEST (shortcut from question). This program calculates the effective volume in front of a point like CR-39 detector for alpha particles of a given energy. The effective volume is defined as the space from where emitted alpha particles can be detected. The algorithm of this program is described in the following text. An alpha particle is emitted with one energy value in the ^{222}Rn chain (5.49 MeV, 6 MeV, or 7.69 MeV) at the distance that is equal to the alpha particle range in air R – naturally the incident energy on the detector is equal to 0. Then the distance, *d*, between the emitting point and point like detector is reduced for a predetermined step and the impact energy on the detector is calculated. Computer programs TRACK_TEST.F90 and TRACK_VISION.F90 written by Nikezic and Yu[1,2] are called now to calculate the track parameters and to determine whether the track is visible or not, based on the incident angle, impact energy, etching conditions, gray level, and visibility criterion. The whole space in front of the detector is systematically examined; the distance is varied with a step less than 0.1 mm, and the incident angle is varied with a step of 1^0. The steps could be setup to be smaller, but that would result in a longer calculation time without a significant increase of the accuracy of the final result. Reduction of the alpha particle energy from the emission point to the detector caused by air was calculated previously using the SRIM 2003 software[20] and the energy–distance dependence is given in the file OUTPUT_A1000.DAT.

The program TRACK_TEST was described earlier, and these details will not be repeated here. This program is used here as subroutine. The program was modified so that all graphical functions and presentations have been canceled, because here only numerical calculations are needed.

By systematic varying of distances and angles, all points in front of the detector were characterized and the effective volume was determined. The program automatically varies the initial alpha particle energy, 5.49 MeV (^{222}Rn), 6 MeV (^{218}Po), and 7.69 MeV (^{214}Po) and the outputs are separately written in files EVCR_1.DAT, EVCR_2.DAT, and EVCR_3.DAT (acronym from effective volume CR-39), which give effective volumes for a specific isotope, respectively. These files consist of five columns. The first column is the incident angle measured from the normal in respect to the surface; the second column is the minimal distance, r_{min}, from where the alpha particle should be emitted to cause a visible track (this distance can be zero), particles emitted closer than r_{min} will not produce a visible track. The third column is the maximal distance, r_{max}, from where the emitted particle can be detected, while particles emitted further than r_{max} will not produce a visible rack. The fourth and fifth columns give the energy detection window, i.e., the minimal and maximal energy between detections occurs for a given incident angle, while outside this window, detection does not take place.

Before executing the program QUEST.F90 the input parameters must be defined in the file INPUTCR.DAT as follows:

- Etching time in hours.
- Bulk etch rate of CR-39 for defined etching conditions, in μm/h.
- Visibility in micrometers (recommended to be about 1), the smallest object that can be distinguished as a track.
- Number of V function, which corresponds to CR-39 used in a real experiment.

B. Discussion about the V function

Many determinations of the V function of a CR-39 detector for alpha particles have been made. The discrepancy between reported results is probably caused by different types of CR-39 used in examinations (prepared from various raw materials or with a somewhat different procedure), as well as by methods applied in measurements. Recently, an excellent critical review of a published V function was given by Hermsdorf,[21] Hermsdorf and Hunger,[22] and Hermsdorf and Reichelt.[23] In this work, the following V functions are built in the software:

$N^0$1 function was published in Durrani and Bull[24] and Green *et al.*[25] in the form

$$V = 1 + (A_1 e^{-A_2 R'} + A_3\, e^{-A_4 R'})(1 - e^{-A_5 R'}) \qquad (2)$$

with constants $A_1 = 11.45$, $A_2 = 0.339\ \mu\text{m}^{-1}$, $A_3 = 4$, $A_4 = 0.044\ \mu\text{m}^{-1}$, and $A_5 = 0.58\ \mu\text{m}^{-1}$; and R' [μm] is the residual range.

$N^0$2 function was published in Brun *et al.*[26] as

$$V = 1 + e^{-A_1 R' + A_4} - e^{-A_2 R' + A_3} + e^{A_3} - e^{A_4} \qquad (3)$$

with constants $A_1 = 0.1\ \mu\text{m}^{-1}$, $A_2 = 1\ \mu\text{m}^{-1}$, $A_3 = 1.27$, and $A_4 = 1$.

Function $N^0$3, taken from Yu *et al.*[27] is in the form

$$V = 1 + e^{-A_1 R' + A_2} - e^{-A_3 R' + A_2} \qquad (4)$$

with constants $A_1 = 0.069\ \mu\text{m}^{-1}$, $A_2 = 1.1784$, and $A_3 = 0.6513\ \mu\text{m}^{-1}$ and $N^0$4 has the same form as function $N^0$3 but with slightly different coefficients[28] $A_1 = 0.06082\ \mu\text{m}^{-1}$, $A_2 = 1.119$, and $A_3 = 0.8055\ \mu\text{m}^{-1}$.

And finally function $N^0$5 is taken from Hermsdorf[21] and has the form

$$V = 1 + \frac{A_1}{(R' + A_2)^{A_3}} \ln(R' + A_4) \cdot (1 - e^{-R'/A_5}) + R'/A_6 \qquad (5)$$

with constants $A_1 = 390$, $A_2 = 2\ \mu$m, $A_3 = 2.35$, $A_4 = 1\ \mu$m, $A_5 = 5\ \mu$m, and $A_6 = 80\ \mu$m.

The user can choose any of these functions by simply changing the last number from 1 to 5 in the file INPUTCR.DAT. Application of another function number will probably generate an error.

This program runs for about 20–30 min (machine dependent). It is not necessary to run it again until the input parameters in INPUTCR.DAT are changed.

III. CALCULATION OF DETECTOR SENSITIVITY

Three different sources contribute to the total track density (and sensitivity): (a) radon and progeny in the chamber air (volume fraction), (b) progeny deposited on the inner chamber wall including the filter opposite to the detector (wall fraction), and (c) progeny deposited on the detector itself (plate out). Three separate subroutines were prepared, one for each source. They are named sequentially from the main program named SENSITIVITY.F90.

To calculate the detector sensitivity, data about the chamber and detector dimensions are needed. It is necessary to define input parameters before execution of SENSITIVITY.F90. They are given in the file INPUTCHAMBER.DAT in the following order: the first parameter is the number of "registered alpha particles;" for example, 10^4 ensures 1% of the relative standard error. Since this calculation is not time consuming, the user can chose a larger number of registered particles. The second line defines the dimensions of the conical chamber, lower radius R_1, upper radius R_2 and height, H all in cm. Since the chamber is conical, R_1 should be smaller than R_2, i.e., $R_1 <= R_2$. If a cylindrical chamber is considered then $R_1 = R_2$. The program will not work if R_1 is larger than R_2 or it would work incorrectly. The user can change any of these parameters. It is not necessary to define the incident alpha particle energy (i.e., isotopes) because the program automatically changes them.

For the reason of simplicity, it is assumed that the detector has a circular shape (although it is difficult to cut a CR-39 detector in the circular form). The user of this program should determine the diameter of a circle that has the same surface area as his detector, which is usually in rectangular form.

A. Subroutine CHAMBER_VOLUME.F90

When the effective volume is determined, calculation of partial sensitivities to a particular progeny can be performed. The subroutine CHAMBER_VOLUME.F90 calculates the sensitivity of CR-39 that is located in the bottom of a conical (or cylindrical) diffusion chamber, assuming that alpha emitters are in the chamber volume. The program calculates partial sensitivities of the CR-39 detector in a given diffusion chamber to radon and progeny, for predetermined etching and readout conditions. This program is executed three times, for all alpha particle energies emitted in the radon chain. The output results are given in System International Units (in m) and in track/cm^2 per Bq day/m^3. They are printed on screen and written in a separate file called OUTPUT.DAT.

B. Subroutine CHAMBER_WALL.F90

Part of radon progeny was deposited on the inner chamber wall before emission of alpha/beta particles. The irradiation geometry is different in comparison to the previous case, and a separate subroutine is used in this case and is also called from SENSITIVITY.F90. The subroutine CHAMBER_WALL.F90 calculates partial sensitivities of the detector to radon progeny deposited onto the inner chamber wall. Input parameters are the same as in the previous case, and they are transferred from the file INPUTCHAMBER.DAT through the main program. This subroutine is executed two times, first with energy of 6 MeV (^{218}Po) and the second time with 7.69 MeV (^{214}Po) with corresponding input files EVCR_2.DAT and EVCR_3.DAT. The output result is partial sensitivity to radon and progeny in System International Units (m) and in track/cm^2 per Bq day/m^3. It is assumed that radon progeny are uniformly deposited on the inner chamber wall. This might not be true, but there is a lack of experimental data on this topic. Some theoretical work claimed that deposition is not uniform[29–31] but this was not implemented in subroutine CHAMBER_WALL.F90. The output is printed on screen and written in a separate file OUTPUT.DAT.

C. Subroutine CHAMBER_PLATE.F90

Some progeny are deposited on the detector itself. This is termed plate out. Progeny are in contact with the detector surface and the irradiation geometry is 2π. However, due to the existence of a critical angle, the detection efficiency is less than 50% and also depends on the etching conditions and readout procedure. The program CHAMBER_PLATE.F90 calculates the sensitivity to progeny deposited onto detector (plate out). This subroutine also uses the same input parameters from file INPUTCHAMBER.DAT that are transferred through the main program. The program also runs two times with energies of 6 MeV (^{218}Po) and 7.69 MeV (^{214}Po) using corresponding effective volumes in files with corresponding input files EVCR_2.DAT and EVCR_3.DAT. It was assumed that progeny are deposited homogeneously onto the inner chamber wall including the detector itself. The results are also given in m and in track/cm^2 per Bq day/m^3. They are printed on screen and written in the same file as above, OUTPUT.DAT.

IV. FINAL RESULTS

As a result of previous executions, the following results were obtained and written in OUTPUT.DAT:

- k_0 partial sensitivity to ^{222}Rn in chamber volume, i.e., in air;
- k_{1a} sensitivity to ^{218}Po in chamber volume, i.e., in air;
- k_{4a} sensitivity to ^{214}Po in chamber volume, i.e., in air;
- k_{1w} sensitivity to ^{218}Po deposited on the chamber wall;
- k_{4w} sensitivity to ^{214}Po deposited on the chamber wall;
- k_{1p} sensitivity to ^{218}Po deposited on the detector (plate out); and
- k_{4p} sensitivity to ^{214}Po deposited on the detector (plate out).

The total sensitivity is calculated as

$$k_{tot} = k_0 + f_1 k_{1a} + f_4 k_{4a} + (1 - f_1) k_{1w} + (1 - f_4) k_{4w} + k_{1p} + k_{4p}, \quad (6)$$

where f_1 is the fraction of ^{218}Po decayed in air and f_4 is the fraction of ^{214}Po decayed in air.

TABLE I. Experiments to compare with presented software.

Reference	Dimensions and shape of the chamber	Dimensions of the detector	Etching conditions	k (m) experiment
M. Mahlobo and S. M. Farid[32]	Conical chamber $R_1 = 2.7$ cm $R_2 = 3.4$ cm $H = 9.5$ cm	2.5×2.5 cm^2 $R_D \approx 1.41$ cm	6 M NaOH, 70 °C, 12 h	0.023
M. S. Garawi[33]	Conical chamber $R_1 = 3.4$ cm $R_2 = 3.85$ cm $H = 4.7$ cm	Not given ($R_D \approx 1$ cm, estimated from Fig. 2 of Ref. 33)	6 M NaOH, 70 °C, 2.5 h	0.014
N. Antovic *et al.*[34]	Conical chamber $R_1 = 2.4$ cm $R_2 = 3.4$ cm $H = 5.3$ cm	$R_D = 1.775$ cm	6.25 M NaOH, 70 °C, 7 h	0.019
A. H. Ismail and M. S. Jaafar[35]	Cylindrical chamber $R_1 = R_2 = 3$ cm $H = 7$ cm	1×1.5 cm^2 $R_D \approx 0.69$ cm	6 M NaOH, 70 °C, 9 h	0.027

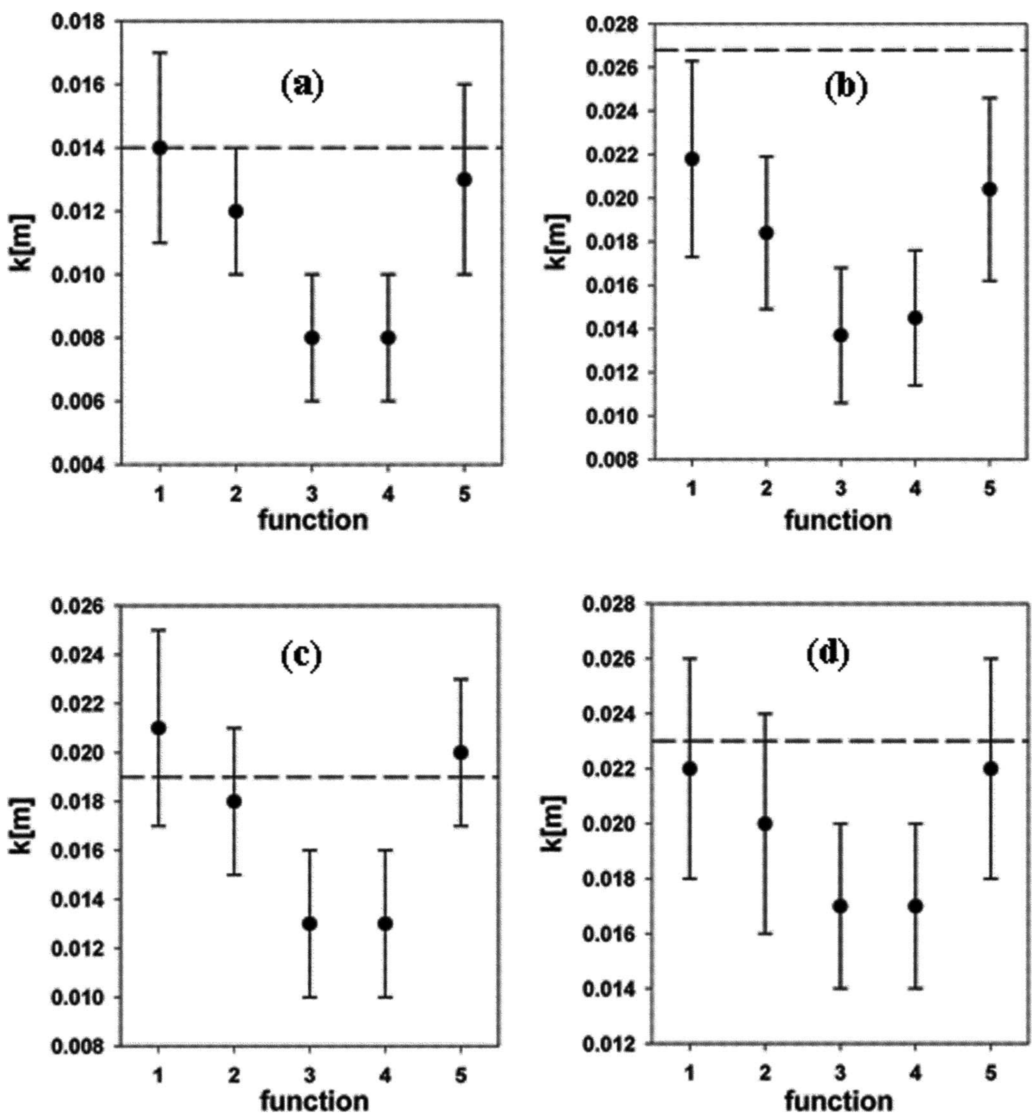

FIG. 1. Comparison of some experimentally obtained values of detector sensitivity and program outputs for five different V functions. Circles (●) represent results obtained by MC Calculation; the dashed lines (– – –) represent experimental values given by (a) M. S. Garawi,[33] (b) A. H. Ismail and M. S. Jaafar,[35] (c) N. Antovic *et al.*,[34] and (d) M. Mahlobo and S. M. Farid.[32]

Two extreme cases exist here: (a) all radon progeny decay in the chamber volume (i.e., in air) before deposition when $f_1 = f_4 = 1$ and (b) all progeny are deposited before decay $f_1 = f_4 = 0$. Sensitivities are given for both extreme cases, and the real one is between these two values. It is reasonable to assume that if ^{214}Po has decayed as fully deposited, $f_4 = 0$ while f_1 is between 0 and 1. This case is also programmed but the user should provide an input value for f_1 after being queried by the program, through the keyboard.

V. COMPARISON WITH EXPERIMENTAL DATA

Detector sensitivity for radon measurements with CR-39 detector was given by many authors. However, usually some of information which are used as input parameters in presented program were missing. For example, removed layer is very rarely given. Somewhere, etching conditions or chamber dimensions were not stated. For these reasons it was difficult to perform comparison with experimental results. However, several articles were chosen Mahlobo and Farid,[32] Garawi,[33] Antovic *et al.*,[34] and Ismail and Jaafar.[35] Basic information of the chamber and etching conditions used by these authors are given in Table I.

In experiments, rectangular detector was more convenient to use, while in calculation it was circular. So, in calculation, circular detectors were assumed with the same surface area as rectangular ones, which were actually used in measurements. Since the removed layer was not given in any of abovementioned paper, it has been estimated based on etching conditions, assuming bulk etch rate $V_b = 1.2\ \mu$m/h which was measured for the etching in 6 M, NaOH at 70 °C.[26,27] In addition, experimental results were given in different units; here all data were recalculated in the same units [m] to facilitate the comparison.

Comparison between experiments and calculation is presented in Figures 1(a)–1(d). Five different V functions were used in all cases (given in ordinate axis). Since the detector sensitivity depends on volumetric fraction, *f*, of ^{218}Po three calculations were performed assuming $f = 1$, 0.5, and 0. In all these figures, experimental result is given as solid horizontal line. Calculation results are presented as scattered points with the uncertainty bar. The upper value of the bar is obtained for $f = 1$, while the lower is for $f = 0$. Scattered points correspond to $f = 0.5$.

Inspection of Figures 1(a)–1(d) shows that functions no. 3 and 4 render smallest values, well below experimental results, while functions no. 1 and 5 gave good agreement with Mahlobo and Farid,[32] Garawi,[33] and Antovic *et al.*[34] The result given by Ismail and Jaafar[35] is well above all calculation data.

According to Figure 1, detector sensitivity obtained by using functions no. 1 and 5 are closest to the experimental data, so these two functions are recommended for application in the software.

VI. CONCLUSION

A computer program for calculating the sensitivity of CR-39 for radon measurements with a diffusion chamber is described in this work. The software can be used for optimization of the diffusion chamber and measurement procedure. If the sensitivity is known from experimental work, this program can be used to determine other parameters related to this kind of detector, like V function for given type of CR-39 detector.

ACKNOWLEDGMENTS

The authors acknowledge the Serbian Ministry of Science, which supported this work through project Grant No. 171021.

[1] D. Nikezic and K. N. Yu, Comput. Phys. Commun. **174**, 160 (2006).
[2] D. Nikezic and K. N. Yu, Comput. Phys. Commun. **178**, 591 (2008).
[3] A. L. Frank and E. V. Benton, Nucl. Instrum. Meth. **109**, 537 (1973).
[4] A. L. Frank and E. V. Benton, *Solid State Nuclear Track Detectors: Proceedings of the 11th International Conference, Bristol, 1981*, edited by P. H. Fowler and V. M. Clapham (Elsevier Science and Technology Books, 1982), p. 531.
[5] R. L. Fleischer, P. B. Price, and R. M. Walker, *Nuclear Tracks in Solids. Principles and Applications* (University of California Press, Berkeley, 1975).
[6] V. A. Nikolaev and R. Ilic, Radiat. Meas. **30**, 1 (1999).
[7] D. Nikezic and K. N. Yu, Mat. Sci. Eng. R **46**, 51 (2004).
[8] H. R. Askari, Kh. Ghandi, M. Rahimi, and A. Negarestani, Nucl. Instrum. Meth. A **596**, 368 (2008).
[9] D. Nikezic, P. Markovic, and Dj. Bek-Uzarov, Health Phys. **62**, 239 (1992).
[10] D. Nikezic, P. Markovic, and Dj. Bek-Uzarov, Health Phys. **64**, 628 (1993).
[11] D. Nikezic, D. Kostic, D. Krstic, and S. Savovic, Radiat. Meas. **25**, 647 (1995).
[12] O. Sima, Radiat. Meas. **25**, 603 (1995).
[13] O. Sima, Radiat. Meas. **34**, 181 (2001).
[14] R. Andriamanatena, G. U. Bacmeister, K. Freyer, R. Ghose, G. Jonsson, T. Kleis, H. C. Treutler, and W. Enge, Radiat. Meas. **28**, 657 (1997).
[15] D. Nikezic and K. N. Yu, Nucl. Instrum. Meth. A **419**, 175 (1998).
[16] M. A. Misdaq, H. Khajmi, F. Aitnouh, S. Berrazzouk, and W. Bourzik, Nucl. Instrum. Meth. B **171**, 350 (2000).
[17] D. Palacios, F. Palacios, L. Sajo-Bohus, H. Barros, and E. D. Greaves, Radiat. Meas. **43**, S435 (2008).
[18] D. L. Patiris, K. Blekas, and K. G. Ionnides, Comput. Phys. Commun. **177**, 329 (2007).
[19] K. P. Eappen, B. K. Sahoo, T. V. Ramachandran, and Y. S. Mayya, Radiat. Meas. **43**, S418 (2008).
[20] J. F. Ziegler, Nucl. Instrum. Meth. B **219–220**, 1027 (2004).
[21] D. Hermsdorf, Radiat. Meas. **44**, 283 (2009).
[22] D. Hermsdorf and M. Hunger, Radiat. Meas. **44**, 766 (2009).
[23] D. Hermsdorf and U. Reichelt, Radiat. Meas. **45**, 1000 (2010).
[24] S. A. Durrani and R. K. Bull, *Solid State Nuclear Track Detection. Principles, Methods and Applications*, International Series in Natural Philosophy Vol 111 (Pergamon Press, Oxford, 1987).
[25] P. G. Green, A. G. Ramli, A. R. Al-Najjar, F. Abu-Jarad, and S. A. Durrani, Nucl. Instrum. Methods **203**, 551 (1982).
[26] C. Brun, M. Fromm, M. Jouffrey, P. Meyer, J. E. Groetz, F. Abel, A. Chambaudet, B. Dorschel, D. Hermsdorf, R. Bretschneider, K. Kadner, and H. Kuhne, Radiat. Meas. **31**, 89 (1999).
[27] K. N. Yu, J. P. N. Ho, D. Nikezic, and C. W. Y. Yip, in *Recent Advances in Multidisciplinary Applied Physics* edited by A. Mendez-Vilas (Elsevier, 2005), p. 29.
[28] K. N. Yu, M. F. Ng, and D. Nikezic, Radiat. Meas. **40**, 380 (2005).
[29] D. Palacios, L. Sajo-Bohus, and E. D. Greaves, Radiat. Meas. **40**, 657 (2005).
[30] D. Nikezić and N. Stevanović, Nucl. Instrum. Meth. B **239**, 399 (2005).
[31] D. S. Pressyanov, Nucl. Instrum. Meth. A **596**, 446–450 (2008).
[32] M. Mahlobo and S. M. Farid, J. Islamic Acad. Sci. **5**(3), 153 (1992).
[33] M. S. Garawi, Radiat. Prot. Dosim. **63**(3), 227 (1996).
[34] N. Antovic, P. Vukotic, R. Zekic, R. Svrkota, and R. Ilic, Radiat. Meas. **42**, 1573 (2007).
[35] A. H. Ismail and M. S. Jaafar, Nucl. Instrum. Meth. Phys. Res. B **269**, 437 (2011).