Journal of Radioanalytical and Nuclear Chemistry, Articles, Vol. 114, No. 1 (1987) 195–202

THE IMPORTANCE OF THE GEOMETRICAL FACTOR IN NUCLEAR ACTIVATION ANALYSIS

G. E. NICOLAOU, N. M. SPYROU, Y. S. KHRBISH

Department of Physics, University of Surrey,
Guildford, Surrey, GU2 5XH (U.K.)

(Received December 12, 1986)

When a beam of radiation is used as a probe in order to study the elemental composition of an object, the factors involved in obtaining maximum detection sensitivity include target homogeneity, beam uniformity and the solid angle subtended between target and detector. Here we have investigated, both theoretically and experimentally, the significance of these factors in an experimental facility for 'in-vitro' prompt gamma-ray neutron activation analysis and an arrangement used in 'in-vivo' activation analysis. The correction factor to the solid angle, to account for non-uniformity, and the optimisation of reaction rate and solid angle are considered.

Introduction

Elemental composition studies based on neutron activation, performed either "in-vitro" or "in-vivo", depend strongly on target homogeneity, the spatial distribution of flux at the irradiation position and the geometrical configuration between target and detecting system.

The first two factors determine the total reaction rate and hence the distribution of the induced activity in the target. In general, the distribution of the activity, which is the product of the spatial distribution of the element in the target and of the flux distribution incident upon the target, is non-uniform.

The geometrical factor is described by the solid angle subtended by the target at the detector. A high detection efficiency is achieved by placing the target close to the detector, thus maximising the solid angle between them. However, this results in the solid angle being very sensitive to the reproducibility of the experimental set up.

The work presented here is confined to the investigation of the effect of the non-uniformity of the induced activity on the geometrical factor and the variation of this factor with position of the target.

Geometrical factor and target non-uniformity

The non-uniform distribution of the induced activity within a target may be the result of either of two cases. In a homogeneous target, within which the element of interest is evenly distributed /1/, the induced activity distribution follows that of the flux profile. However, as the flux profile is not uniform, the irradiation results in the non-uniformity of the activity in the target (Figure 1). In the case of an inhomogeneous target, the activity distribution is the product of the flux profile and the elemental distribution. Assessment of the non-homogeneity of a thin target may be made by scanning it with a charged particle probe, e.g. PIXE /2/, with the size of the probe being considerably smaller than the size of the target.

Elsevier Sequoia S. A., Lausanne
Akadémiai Kiadó, Budapest

The effect of the non-uniformity of induced activity on the geometrical factor was investigated in relation to experiments in Prompt Gamma-ray Neutron Activation Analysis, as shown in Figure 1. A collimated beam of thermalised neutrons impinges upon a thin, disc-shaped, homogeneous target. The emitted gamma-rays following neutron capture (n,γ) reactions are detected by a Ge(Li) detector at 90° to the beam axis. It was found, using neutron radiography and activation of gold foils, that the beam profile consists of two regions: a circular region of high uniformity and an annulus of lower average flux. Irradiation results in the creation of the corresponding regions 1 and 2 with activities proportional to the impinging flux (Figure 1).

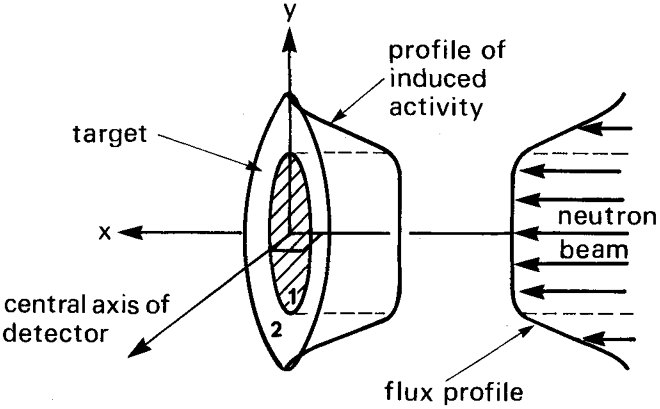

Fig. 1. Neutron beam-target-detector geometrical configuration

The detector response following irradiation is proportional to $(A\times\Omega)$, where A is the total activity induced in the target and Ω the solid angle the target subtends at the detector. If A1 and A2 are the activities induced in the two regions, then the detector response D is

$$D \propto (A1\times\Omega1+A2\times\Omega2)$$

where $\Omega1$ and $\Omega2$ are the solid angles the circular and the annular regions subtend with the detector. If the non-uniform distribution of the activity in the target has no effect on the detector response, then

$$A\times\Omega = A1\times\Omega1+A2\times\Omega2 \qquad \dots\dots\dots\dots \qquad (1)$$

otherwise Ω has to be multiplied by a correction factor, f, in order to account for the non-uniformity; equation (1) then gives

$$f\times\Omega = \frac{A1\times\Omega1+A2\times\Omega2}{A1+A2}$$

and if the relative ratio of the activities $g = (A1/A2)$, where g: $[0,\infty]$, then

$$f\times\Omega = \frac{g\times\Omega1+\Omega2}{1+g} \qquad \dots\dots\dots\dots \qquad (2)$$

If $g = 0$, the activity being concentrated in the annulus, $(f\times\Omega) = \Omega2$; if $g \rightarrow \infty$ the activity is concentrated in the circular region and $(f\times\Omega) \rightarrow \Omega1$. These extreme cases indicate that such a correction may be necessary depending on the values of g and the solid angles.

The experimental verification of such a correction was performed by simulating the configuration shown in Figure 1. Two concentric discs, creating the annular and circular regions, were placed above a NaI(Tl) detector. The discs were filled with Cs-137 solutions to represent the induced activity of the two regions. For g = 3, 76500 (±330) counts were found in the Cs-137 photopeak. Whereas, when the same amount of activity was uniformly distributed over the whole area the count was 74557 (±320). The ratio of the two counts was found to be 1.026 ± 0.003 and should be equal to the ratio of the corresponding solid angles. This occurs only when the solid angle for the non-uniform distribution is corrected using equation (2); the solid angles were obtained using a Monte Carlo method /3/. The ratio of the solid angles was calculated to be 1.029 ± 0.002.

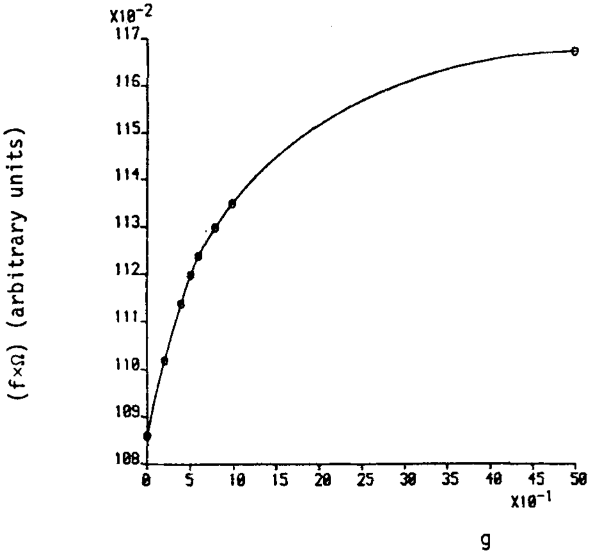

Fig. 2. Variation of (f×Ω) with g

The variation of $(f\times\Omega)$ with g, for the experimental set up considered is shown in Figure 2. The graph confirms the limiting cases, i.e.

as $g \rightarrow 0$ $(f\times\Omega) \rightarrow \Omega2$, where $\Omega2 = 1.085$

and as $g \rightarrow \infty$ $(f\times\Omega) \rightarrow \Omega1$, where $\Omega1 = 1.184$

When $g = r^2/(R^2-r^2)$, where r is the radius of the circular region and $(R - r)$ is the width of the annulus and in our example $g = 0.65$, a uniform distribution of activity is obtained since the specific activity within each region is the same, and $(f\times\Omega) \rightarrow \Omega$, where $\Omega = 1.126$.

Geometrical factor and target position

The variation of the solid angle, subtended between the target and the detector, with target position was studied in relation to the configurations we use for 'in-vitro' and 'in-vivo' experiments.

(a) 'In-vitro' case

The target in the 'in-vitro' set up shown in Figure 1 can be rotated around the y-axes and be oriented at any angle, between 0° and 90°, to the central axis of the beam. It has been established that maximum detector response occurs for an angle of 90°, when the target is perpendicular to the beam axis and subtends a maximum solid angle with the detector /4/.

The variation of the solid angle with target displacement along the x-axis, and for 90° rotation angle, is 5% and 2% per 10 mm displacement for target-to detector distances, H, of 50 mm and 100 mm, respectively. The result clearly demonstrates the sensitivity of the geometrical factor to target displacement for the smaller values of H.

The combined effect of target rotation and non-uniformity on the geometrical factor is shown in Figure 3 for two different values of H and for $g = 5$. The variation, for the non-uniform case, of the corrected $(f{\times}\Omega)$ and uncorrected (Ω) solid angle of the target indicates the need of a correction as the rotation angle approaches 0° and H decreases.

(b) 'In-vivo' case

The geometrical factors involved in partial-body 'in-vivo' neutron activation were investigated for our activation system /5/, which is schematically shown in Figure 4.

When the elemental content of an organ is being determined 'in-vivo', for example cadmium in liver /6,7/, the detector is placed as close to the organ as possible for maximum solid angle and hence detection sensitivity. The detector is usually collimated in order to minimise the background and any interference of the element of interest from other organs. A volume, V, which is the intersection between the field of view of the collimator and neutron beam exist within the phantom and the detector may 'see' only part of the organ. Clearly an optimisation of the detector position is essential for maximum detection sensitivity.

A phantom, representing the mid trunk of the body, containing a homogeneous solution of cadmium was irradiated by neutrons. The prompt 559 keV cadmium photopeak area, S, and the underlying background, B, were recorded using a collimated Ge(Li) detector. The normalised variation of the signal, S, and signal-to-noise ratio $(S/\sqrt{B})$, along the phantom is shown in Figure 5 and reveals such an optimum position at 38 ± 2 mm.

The detector response depends on the volume of intersection and its solid angle with the detector as well as on the total reaction rate within this volume. Best detection sensitivity occurs when the product of the reaction rate, in the volume, and the solid angle of the volume is maximum. These two factors were investigated theoretically for the experimental set up as follows.

The phantom was divided into thin sections along its length. For a given position of the detector, the contribution of each section to the detector response is the product of the reaction rate within it and the solid angle it subtends with the collimated detector. The solid angle was evaluated using a Monte Carlo method /8/. The variation of the solid angle (Ω) of each section, the reaction rate (R) within it and its contribution $(R{\times}\Omega)$ to the detector response, as a

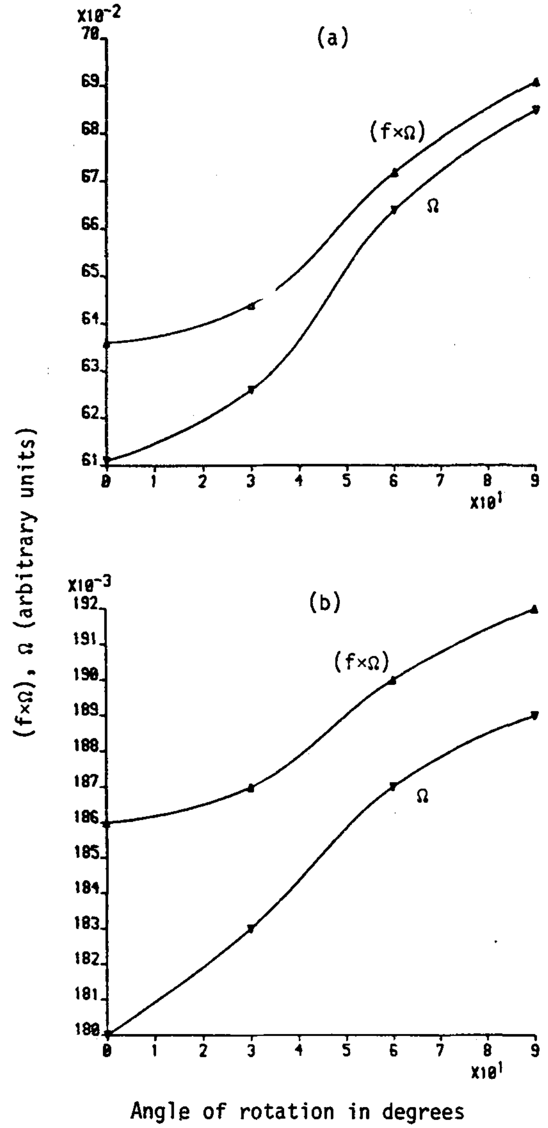

Fig. 3. Variation of $(f\times\Omega)$ and Ω with angle of rotation of the target for (a) H = 50 mm and (b) H = 100 mm

function of depth in the phantom, is shown in Figure 6. The area under the curve $(R\times\Omega)$ gives the reaction rate in the phantom which will be detected. The variation of this area for different positions of the detector as a function of depth in the phantom is shown in Figure 7. It reveals an optimum position, for maximum detection signal, at 40 ± 2 mm, which is in good agreement with the experimental value.

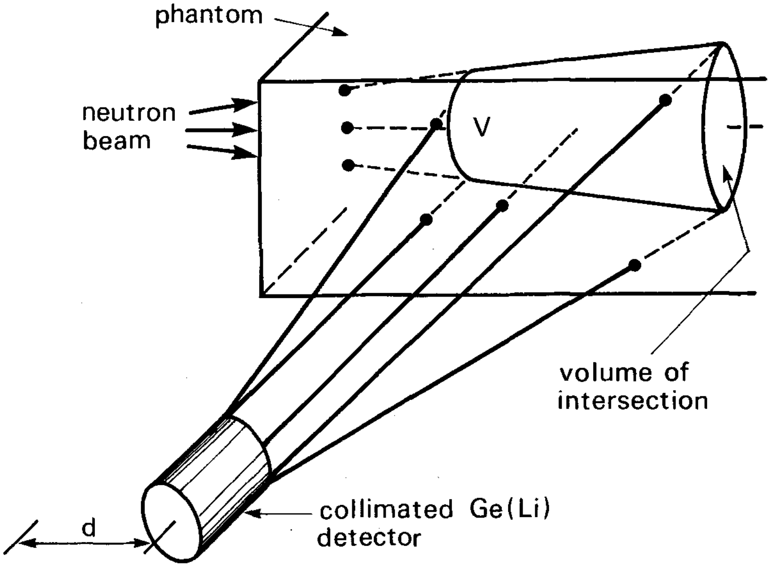

Fig. 4. Experimental set-up for 'in-vivo' neutron activation analysis

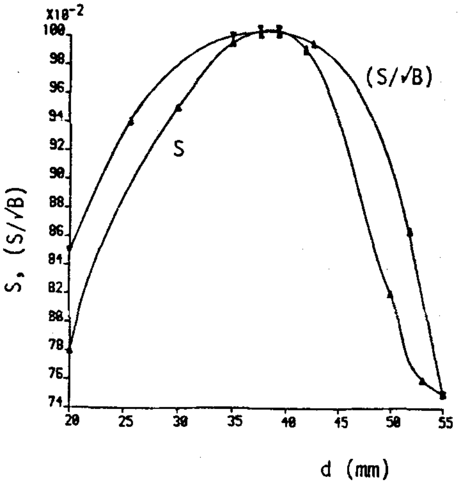

Fig. 5. Normalised variation of signal (S) and signal-to-noise ratio $(S/\sqrt{B})$, along the phantom

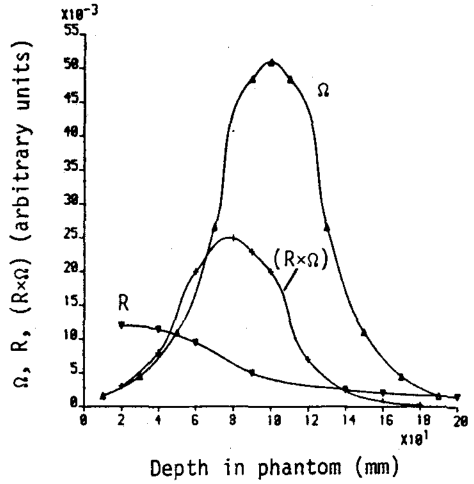

Fig. 6. Variation of Ω, R and (R×Ω) as a function of depth in the phantom

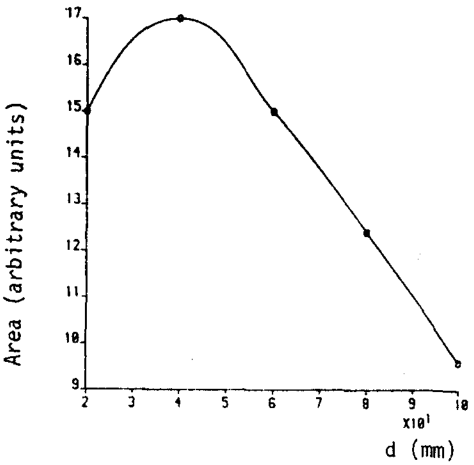

Fig. 7. Variation of the area under the curve (R×Ω) for different positions, d, of the detector

The theoretical method gives no information about the signal-to-noise ratio. However, as this increases with increasing signal, the method just described can be used for optimisation of the detector position for maximum detection sensitivity.

Conclusions

The effect of the non-uniformity of the target activity on the geometrical factor and the variation of this factor with position of the target have been investigated for 'in-vitro' Prompt Gamma-ray Neutron Activation Analysis.

The essentiality of applying a correction factor to the solid angle the target subtends with the detector, in order to account for non-uniformity, was verified both theoretically and experimentally. This factor depends strongly on the solid angles involved and the activity distribution in the target and therefore an accurate determination of these two parameters is required.

When the effect of target position and non-uniformity on the geometrical factor was investigated a measure of the sensitivity of the solid angle to target displacement for small separations of target-detector distance was obtained. The combined effect of non-uniformity and angle of rotation of the target showed that an error of 4% is introduced to the geometrical factor when the target approaches an angle of rotation 0° and no correction for non-uniformity is made. This error decreases to < 1% when the target is perpendicular to the beam. Therefore, the advantage of having the target in the latter position is twofold: the solid angle subtended with the detector is maximum and the importance of the correction factor decreases.

The geometrical factor involved in the 'in-vivo' set-up shows the influence of the volume of intersection, in terms of its solid angle with the detector and the reaction rate within it, on the detection sensitivity. Clearly the maximum product of the reaction rate and the solid angle is required for best detection sensitivity.

*

The post-doctoral research grant provided by the Onassis Foundation, Greece, to one of the authors (GEN) is gratefully acknowledged.

References

1. K. HEYDORN, Neutron Activation Analysis for Clinical Trace Element Research, Vol. 1, CRC Press, Florida, USA, 1984.
2. D. M. ALBURY, N. M. SPYROU, Nucl. Instr. Methods, A242 (1986) 635.
3. L. WIELOPOLSKI, Nucl. Instr. Methods, 143 (1977) 577.
4. Y. S. KHRBISH, N. M. SPYROU, Geometrical Factor in Absolute Measurements Using Prompt Gamma-ray Activation Analysis, The International Conference on Analytical Chemistry in Nuclear Technology, Karlsruhe, FRG, 1985.
5. N. M. SPYROU, I. P. MATTHEWS, J. Radioanal. Chem., 61 (1981) 195.
6. G. E. NICOLAOU, I. P. MATTHEWS, L. G. STEPHENS-Newsham, N. M. SPYROU, J. Radioanal. Chem., 71 (1982) 519.
7. J. B. KRANEL, M. A. SPEED, B. N. THOMAS, H. BUDDELEY, B. J. THOMAS, Int. J. Appl. Radiation, Isotopes, 31 (1980) 101.
8. G. E. NICOLAOU, Ph. D. Thesis (Physics), University of Surrey, UK, 1983.