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Modeling the transmission of beta rays through thin foils in planar geometry

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HIGHLIGHTS

- A mathematical model of electron transport in planar geometry is developed.
- The model is based on the plane source concept.
- The efficiency of plane sources is computed using Monte Carlo method.
- A simple function for the plane source efficiency is obtained by curve fitting.
- Applications of the mathematical model are also presented.

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ABSTRACT

This paper is concerned with the modeling of the transmission of beta rays through thin foils in planar geometry based on the plane source concept, using Monte Carlo simulation of electron transport and least squares fitting. Applications of modeling results for calculating the efficiency of large-area beta sources, transmission coefficient of beta rays through thin foils and the beta detection efficiency of large-area detectors used in surface contamination measurements are also presented.
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1. Introduction

The transmission of beta rays through thin absorbers in planar geometry is quite different from the case of collimated beams. This is due to the fact that the emission of beta particles is isotropic and the majority of trajectories through the absorber are longer than the thickness of the absorber. The geometry effect on experimentally determined transmission curves (Jansen and Klein, 1996) and a heuristic approach for calculating roughly the attenuation of beta-rays in thin absorbers in planar geometry have already been reported (Haemers et al., 2007). Monte Carlo simulation of the electron transport through thin foils in planar geometry was also performed for determining the efficiency of large-area beta sources (Berger, 1998; Svec et al., 2006; Stanga et al., 2011).

The mathematical modeling of the transmission of beta rays through thin foils in planar geometry is useful for a range of applications such as standardization of large-area sources (ISO, 2010; Berger et al., 1996), calibration of contamination monitors (IEC, 2002), evaluation of surface contamination (ISO, 1988; ISO, 1996) and gross beta counting (ISO, 1992; Pujol and Suarez-Navarro, 2004). By mathematical modeling, the problems from these areas are translated into tractable mathematical formulations whose theoretical and numerical analysis provides insight, answers and guidance useful for these applications.

This paper deals mainly with the modeling of the transmission of beta-rays through thin foils in planar geometry based on the plane source concept (Berger et al., 1996), using Monte Carlo simulation of electron transport and least squares fitting. Thus, the efficiency of plane sources located at different source depths was computed by Monte Carlo method and Monte Carlo data were fitted by the linear least squares method with a polynomial function which depends on the square root of the source depth.

As a result of modeling, mathematical tools were developed for calculating the efficiency of large-area beta emitting sources, the

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transmission coefficient of beta rays through thin foils and the beta detection efficiency of large-area counters. These are powerful tools with many applications in the areas mentioned above. Thus, the integral equation for calculating the source efficiency provides a simple relationship between the surface emission rate and the activity of large-area beta emitting sources. This is in contrast with the general opinion that there is not a simple and known relationship between these quantities (ISO, 2010). The same integral equation can be used for evaluating the surface contamination by calculating the efficiency of beta contamination sources. The standard ISO 7503-1 provides two suggested default values for the efficiency of beta contamination sources but they do not have a strong theoretical basis (ISO, 1988).

Novel methods of measurement can be developed by using the integral equations for calculating the source efficiency and the transmission coefficient. A new method, based on these equations, for determining the activity of large-area beta reference sources constructed from anodized aluminum foils has already been reported (Stanga, 2014). The integral equation for calculating the detection efficiency can be used for investigating under which conditions the calibration of surface contamination meters on the basis of activity per unit area is useful.

In September 2014 the three year duration Joint Research Project "MetroDecom-Metrology for decommissioning nuclear facilities" started in the frame of the European Metrology Research Programme (EMRP). One of specific objectives of the project is to improve the accuracy and traceability of surface beta contamination measurements. The modeling of the transmission of beta rays through thin foils in planar geometry is the starting point in the achievement of this objective.

2. Transmission of beta-rays emitted by plane sources through thin foils

2.1. Efficiency of plane sources

We consider the large-area source shown in Fig. 1 without the covering foil. In this planar geometry the source substratum of thickness Δ is placed on a backing plate both being constructed from the same material of circular shape having identical radii. The activity is incorporated into the top surface of the source substratum resulting in a source which has a thin active layer and a circular shape. The backing plate is thick and the radius of the active layer is small to prevent emission of the beta radiation through the back and the side of the source. We used a circular type source but the results of this paper remain valid for any type of planar source.

For a point source of infinitesimal volume assumed to be located at the position (*x, y, z*), its emission rate in 2π, *E(x, y, z) dxdydz*, is defined as the rate of beta particles that emerge from the top surface of the large-area source in a 2π solid angle. The emission in 2π of the source results from the interplay of two factors. On the one hand, emission is increased due to the backscattering of beta particles by the backing plate, while on the other hand, the emission is decreased due to the absorption of beta particles by the substratum material. The efficiency of the point source is defined as the ratio between its emission rate *E(x, y, z) dxdydz* and its activity *Λ(x, y, z)dxdydz* (assuming that the emission probability of beta particles is 100%). It is evident that the efficiency of the point source does not depend on the coordinates *y* and *z*. Under these conditions, the efficiency, $\varepsilon_p(x)$, of the plane source located at the depth *x* can be defined as

$$\varepsilon_p(x) = \frac{E_p(x)}{\Lambda_p(x)} \tag{1}$$

where $\Lambda_p(x) = \iint_S \Lambda(x, y, z)dydz$, $E_p(x) = \iint_S E(x, y, z)dydz$ (S is the surface of the plane source), $\Lambda_p(x)dx$ and $E_p(x)dx$ represent the activity and the emission rate in 2π of the plane source. In case that the substratum material is different from the material of the backing plate, $\varepsilon_p(x, \Delta)$ depends on both *x* and the thickness Δ of the substratum material. This is due to the fact that the electrons are backscattered by a double-layered material composed of a backing plate (with the thickness higher than the backscattering saturation thickness) and a thin layer of variable thickness containing the substratum material (see chapter 3). In this case, Eq. (1) becomes

$$\varepsilon_p(x, \Delta) = \frac{E_p(x, \Delta)}{\Lambda_p(x)} \tag{2}$$

In practice, large-area beta sources are often constructed as it is shown in Fig. 2. This planar geometry is equivalent with the geometry from Fig. 1 when the substratum and backing plate are made from the same material. In case that these materials are different, the efficiency of a point source located at the position (*x, y, z*) depends on the coordinates *y* and *z* located near the source edge. Consequently, the efficiency of the plane source from the depth *x* depends on the coordinates *y* and *z*. However, this edge effect can be neglected if the atomic numbers of materials are close and/or the source radius is much longer than the maximum range of beta-rays in the substratum material.

As mentioned above, Eq. (1) is valid for nuclides that emit beta radiations with emission probability of 100% such as ^{14}C, ^{147}Pm, ^{60}Co, ^{36}Cl and ^{90}Sr–^{90}Y. In case of nuclides that emit both beta particles having a continuous energy spectrum and conversion electrons having discrete energies E_i with emission probabilities f_i (*i*=1, 2,…,n), the plane source efficiency can be written as

$$\varepsilon_p(x) = \frac{E_p(x)}{f_T \cdot \Lambda_p(x)} = \frac{E_b(x) + E_{ce}(x)}{f_T \Lambda_p(x)} = \frac{f_b \varepsilon_{pb}(x) + f_{ce} \varepsilon_{pce}(x)}{f_T} \tag{3}$$

where $E_b(x)$, f_b and $\varepsilon_{pb}(x)$ are, respectively, the emission rate in 2π, the emission probability and the plane source efficiency corresponding to beta particles, $E_{ce}(x)$, f_{ce} and $\varepsilon_{pce}(x)$ are, respectively, the emission rate in 2π, the total emission probability and the plane source efficiency corresponding to conversion electrons, $f_T = f_b + f_{ce}$ and $E_p(x) = E_b(x) + E_{ce}(x)$. It should be noted that Eq. (3) reduces to Eq. (1) when $f_b = 1$ and $f_{ce} = 0$. The efficiency, $\varepsilon_{ce}(x)$, is given by

$$\varepsilon_{ce}(x) = \frac{E_{ce}(x)}{f_{ce} \Lambda_p(x)} = \frac{1}{f_{ce}} \sum_{i=1}^{n} f_i \varepsilon_{pi}(x) \tag{4}$$

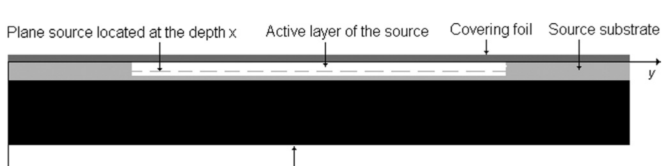

Fig. 1. Schematic view of a large-area source covered by a thin foil.

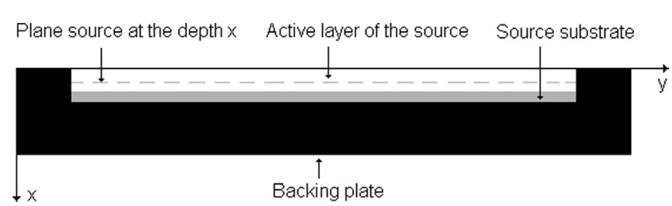

Fig. 2. Schematic view of a new type of large-area source.

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