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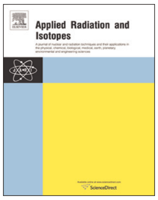

New analytical solution to calculate linear absorption coefficients of beta radiations

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HIGHLIGHTS

- New analytical model of beta radiation transmission curve in 2π geometry has been proposed.
- Linear absorption coefficients in aluminum and Mylar were calculated for 19 radionuclides.
- An empirical relationship between the calculated range parameter and average energy of beta radiation emitted by radionuclides was established.

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ABSTRACT

The paper deals with an alternative model of beta radiation transmissions through attenuation layers and brings another analytical description of this phenomenon. The model is validated with a reliable data set and brings a possibility to calculate characteristic material parameters with low uncertainties. Using no correction factors, these calculations can be considered fundamental and inspiring for further research in the field.

1. Introduction

Attenuation is a significant physical phenomenon accompanying the movement of charged particles through matter. Traveling beta particles gradually loose their energy by collisions with atoms and change their direction by multiple scattering. Resulting complicated paths with finite ranges can be evaluated statistically and characterized by various parameters related to the particle energies, matter composition and experimental conditions.

Modeling of absorption of beta radiation started in the time of its discovery more than 100 years ago and the most distinguished scientists were involved in this topic. An interesting historical review concerning this subject was published lately by (Franklin, 2002). That time discussions concerned the interpretation of results of absorption experiments obtained with two different kind of radiations namely monoenergetic electrons which followed approximately a linear absorption law and electrons with continuous spectra of energies that subjected to exponential relationships in spite of opposite views of the scientific community. J. A. Grey in 1910 finally terminated disputes and concluded that (cited by Franklin 2002)

1. β-rays, which are absorbed according to an exponential law, are not homogeneous (i. e. they are polyenergetic)
2. β-rays must fall in velocity in traversing matter.

The instrumentation used for data acquisition was rather primitive from contemporary points of view, using photographic plates and gold-leaf electroscopes for radiation detection (Flakus, 1981). No device able to count individual particles existed in that time and only gross ionization effects were registered. Energy spectra of collimated beams were analyzed in magnetic fields but the low detector sensitivity was the main limiting factor. Due to different characteristics of ancient and contemporary detectors the former and contemporary results are not directly comparable.

Nevertheless, the question of attenuation or transmission curves has not been solved completely yet. It has been observed

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that the real transmission curves at their low ends really converge to exponentials with their characteristic parameter – the linear absorption coefficient – almost identical with that obtained for collimated beams. This observation is usually projected in analytical descriptions by various corrections improving the exponent to suit the experimental data in wide range of transmissions. This is the case of an older work of Baltakmens (1970) who analyzed deeply absorbed radiations (experimental efficiencies down to about 1%). Transmission curves are also referred to as absorption curves although they are complementary to attenuation and absorption curves (Subba Rao, 1966). But terminology is not regarded as a problem as long as it is not confusing. It is generally accepted that β-particle transmission curves are not pure exponentials and their shape changes e.g. with the distance of the source and detector to the absorber (an attenuator), with the shape of the β-particle energy spectrum, etc. (L'Annunziata, 2007). A similar statement can be said about monoenergetic electrons, the absorption of which was first considered linear. Subba Rao (1966) developed a simple formula which perfectly fits this problem. Its analytical form of the Fermi function type is, however, far from linear being combined of a couple of exponential functions. Several authors tried to describe transmission relationships by various empirical functions like polynomials and trigonometric formulae (Lukyanov, 1963) that were not widely accepted. Analytical description of collision and radiative stopping power components is complicated and usually related to the particle energy using various diagrams (Shultis and Faw, 2008) or formulae (Tabata et al., 1972). It can be summarized that analytical descriptions of beta radiation transmission curves vary from case to case and no generally preferred analytical model exists so far.

This brief overview might indicate that there is no reason to insist on using an exponential function for transmission curves of beta radiation. Yet, at least one practical reason exists based on its widely used single parameter – the linear absorption (attenuation) coefficient which is characteristic for both radiation and absorbing material properties. Its information capability is so valuable that it is worthwhile to preserve the exponential as a basis for more sophisticated mathematic constructions describing real situations. If the exponential function characterized by a unique value of the linear attenuation coefficient could be considered as inherent to processes accompanying interactions of beta radiation with matter it would greatly facilitate the evaluation of observations under different conditions and experimental arrangements. Any analytical description of real beta radiation transmission processes should somehow converge to this exponential which unifies various approaches to this problem and its solution. And, the common linear absorption coefficient should remain the determining parameter of this exponential.

Up to now various methods for the determination of linear attenuation coefficients have been developed. Some papers are devoted to numerical (Yi et al., 1998; Mahajan, 2012) or partly theoretical (Burek and Chocyk, 1996; Gürler and Yalçin, 2005) procedures while others deal more with experimental data. Correlations between values of the linear absorption coefficient and other corresponding beta particle characteristics like maximum or average energies, ranges etc. were observed. Baltakmens (1977) related absorption coefficients to both the maximum and/or average energies of the beta energy spectrum and finally found a better correlation with the area under the spectrum which is proportional to the mean particle energy per disintegration including the spectrum shape. Some effort has been devoted to obtain values of absorption coefficients theoretically, yet a comprehensive and reliable source of information about absorption coefficient values in various materials is still unavailable. A generalized empirical equation for the transmission coefficient of electrons Tabata and Ito (1975) developed in a rather complex way from the basic formula proposed by Rao accounts for the energy of electrons and the material composition however, resulting values are obtained with large uncertainties. Radiation protection oriented papers like Turner (2004) usually use the continuous slowing down approximation concept (CSDA) and beta particle ranges instead of absorption coefficients. There is, again, a clear correlation between the CSDA and absorption coefficient values but the relationship cannot be fixed by a simple function because the CSDA values deals with monoenergetic electrons and the absorption coefficients concern beta radiations including variations in their spectral distribution.

So far most of the suggested models of beta attenuation in literature do contain an exponential function of the absorber thickness as a central characteristic component. It is correct for so called "good geometry", the term introduced by (Thontadarya and Umakantha, 1971) for well collimated narrow beam of electrons pointed towards a not necessary large detector. However, radioisotope sources emitting beta particles create spherically symmetric and isotropic radiation fields while detectors are usually flat and variable in shapes and dimensions. Various authors tried to cope with the problem different ways. Janßen and Klein (1996) described deviations from a pure exponential law at real conditions of large area source measurements extending the absorption coefficient by a simple two-parameter polynomial term. Stanga et al. (2011) also used the linear absorption coefficient as a parameter of an empirical function of the penetrating depth or the absorption material thickness respectively, corrected by a special polynomial term. Yi et al. (1998) compared two older semi-empirical models with their own calculated data and found reasonable agreement for "good geometry" and deeply absorbed radiation (transmissions lower than 0.2). They pointed out that the attenuation coefficient values depend on the transmission curve range selected for their determination. Best fit is achieved at low transmissions ($<$ 20%) when the calculated apparent attenuation coefficients approach "true" values. A short technical note was published by Thontadarya (1985), who recommended to determine electron ranges from measurements at transmissions as low as 0.1%. In other words, in order to obtain correct mass attenuation coefficient values, the low attenuated region of the transmission curve was ignored and only quasi-linear parts at its lowest end in semi-log coordinates were taken into account. The reason may have several aspects: (a) beta spectra of various radionuclides have different shapes but all of them resemble each other at their descending parts close to the maximum energies, (b) 80% and more particles are already removed from the radiation field at the end of the transmission curve and the remaining high energy particles are partly collimated by passing the shortest paths in the thick absorber thus representing a radiative "arrowhead" and (c) high energy particles at the end of the spectrum cover a narrow band of energies only and so they are "almost monoenergetic". However, an objective and complex explanatory model should cover the absorption process as a whole beginning from lowest possible absorptions and lowest possible energies occurring in the emitted spectrum of beta particles.

Research in our national laboratory of metrology has been motivated by an effort to find a method for testing large area standard activity sources. In our first paper on this topic no specific attenuation function were used, but numerically smoothed experimental data in small intervals of artificially changed attenuation conditions were numerically approximated with a local parabola (Švec et al., 2006). The procedure resembled the use of spline functions. Calibration curves were constructed from these partly smoothed calibration data and their numerical derivatives. A more advanced method has been developed and published recently, based on the exponential function modified according to Stanga et al. (2011) but a different way of experimental data