THE ENERGY DEPOSITION PROFILE of 0.1-3.0 MeV ELECTRONS in NaCl

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Abstract

An analysis is presented of experimental and theoretical data of energy loss profiles and energy deposition in thick targets irradiated with MeV-energy electrons. A simple approximate calculation is proposed for the energy deposition profile of a perpendicular beam of 0.1-3 MeV electrons. It is shown that the build-up phenomenon has a significant effect on the energy deposition profile in thick samples. We present an experimental investigation of the energy deposition profile of 0.5 MeV electrons in 0.2 - 0.8 mm thick NaCl platelets. The distribution of the absorbed dose was determined with differential scanning calorimetry by measuring either the latent heat of melting of the radiation-induced Na-precipitates.

INTRODUCTION

One should distinguish two different quantities: the energy losses and energy deposition by electrons in a target. The energy loss is the specific energy, which is lost by incident electrons of the beam at a given depth, whereas the energy deposition is the specific energy dissipated by primary, δ-, secondary, and other high-energy electrons at a given depth. The energy loss of monoenergetic electrons due to ionization and excitation processes in thin targets can be described with the Bethe-Bloch formula [1]. Seltzer and Berger [2] published the energy loss tables, the density correction δ and experimentally derived values of the mean excitation energy I (for NaCl is I = 175.3 eV).

The calculation of energy losses by electrons in a thick target is a rather complex problem that requires a sophisticated approach. The main difficulty arises from the back scattering and multi-scattering of electrons in matter. Hence, it is necessary to take into consideration the role of δ-electrons in the process of transfer of energy, when calculating the energy deposition profile. Spencer [3], Rao [4], and Kobetich and R. Katz [5] performed extended analytical calculations of the energy loss profiles for an incident electron beam, which is directed perpendicularly to a flat surface.

Energy loss profile

Spencer [3] has carried out the most complete calculations of the energy dissipation of perpendicular electron beams. Rao [4] derived a simple formula for the fraction of the incident electrons of energy E transmitted by an absorber of thickness t:

$$\eta = \frac{1+\exp(-gh)}{1+\exp[g(t/R-h)]} \qquad (1)$$

where $g = 9.2Z^{-0.2} + 16Z^{-2.2}$ and $h = 0.63\,Z\,/\,A + 0.27$.

The dependence of the transmission η of a 0.5 MeV electron beam in NaCl on the sample thickness t, calculated on the basis of Eq.1 is shown in Fig.1.

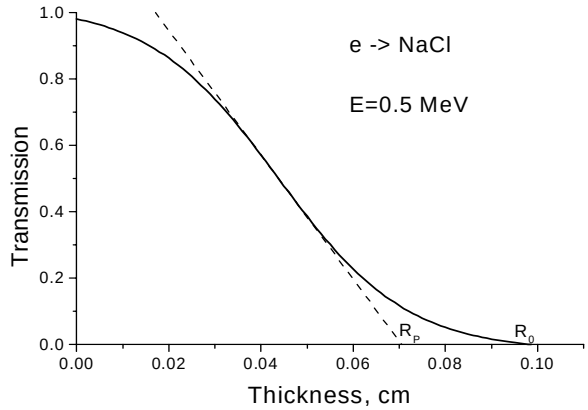

Figure 1. Dependence of beam transmission on the thickness of NaCl samples.

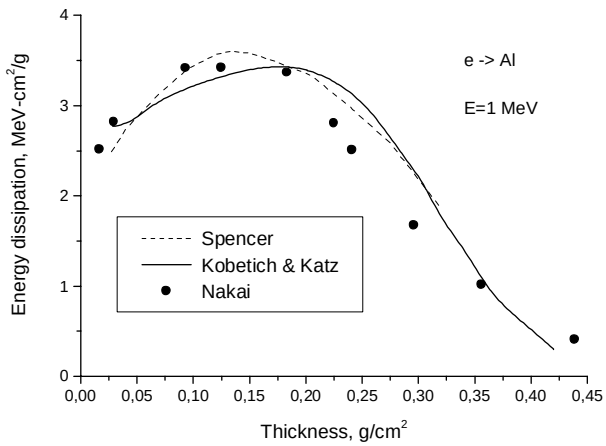

Figure 2. Energy dissipation profiles in aluminum, calculated by Spencer; Kobetich and Kaz; solid circles - experimental values from Nakai [6].

The point where the extrapolation of the linear region intersects the x-axis is referred to as the practical (or extrapolated) range R_P, whereas the point where the tail intersects x-axis is known as the maximum range R_0.

The energy loss profile of a perpendicular incident electron beam can be calculated (see [5]):

$$S = \frac{d[\eta E(R-t)]}{dt}. \qquad (2)$$

Here $E(R)$ is the energy-range relation.

The energy loss profile has a maximum (see Fig.2), which is due to the competition of two trends: the increase of specific energy losses as a function of the depth and the decrease of the electron density in the beam.

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Range-energy relation

The maximum range of the electrons in matter can easily be calculated in the continuous-slowing-down-approximation (CSDA):

$$R_0(E) = \int_0^E dE' / \left(\frac{dE'}{dx}\right)_{tot}, \qquad (3)$$

here $S(E') = \left(\frac{dE'}{dx}\right)_{tot}$ is the value of the total energy losses for an electron with energy E'. R_0 is the total path length required to slow the electrons down to rest. Extended tables of CSDA ranges of electrons in many materials and compounds were published by Seltzer and Berger [2]. Katz and Penfold [7] approximated the practical ranges for pure aluminum with the following formula, which is valid in the energy interval 0.01 – 3 MeV:

$$R_{Al} = 0.421\, E^{1.265 - 0.0954 \ln E}, \qquad (4)$$

here R_P is the range in g/cm^2 and E – the energy of the electrons in MeV.

ENERGY DEPOSITION PROFILE

Some experimentally observed energy deposition profiles for aluminum are shown in Fig.3 [8]. The energy deposition profiles as well as the energy loss profiles show a pronounced maximum.

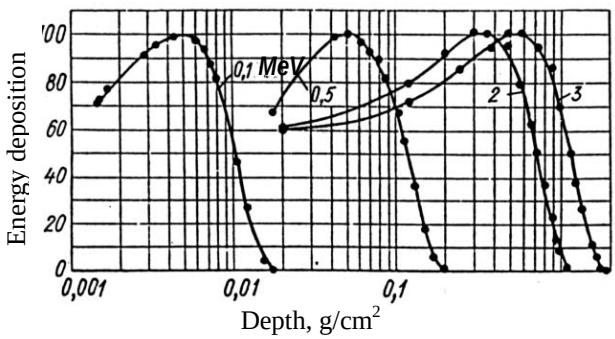

Figure 3. Energy deposition profiles in aluminum [8].

Calculation of the electron beam energy deposition in a target is a rather complicated problem because of multiple scattering of electrons by atoms and the appearance of δ-electrons. So, for a quick evaluation we have developed a simple semi-empirical method for the calculation of the electron beam energy deposition $Q(x)$, based on dependable, measured energy deposition profiles for a parallel electron beam in aluminum.

Universal profile approximation

It is seen from Fig. 3 that in the 100 KeV - 3MeV energy range, the energy deposition profile $Q(x)$ can be easily scaled in x by the value of the practical range $R_P(E)$ and expressed in terms of the universal function $P(\xi)$ (see Fig.4)

$$P(\xi) = \frac{1.437}{\{ch[0.95(2.295\xi - 1)]\}^{1.8}[0.5 + 1/(2.7 - 2.295\xi)]} \qquad (5)$$

Here ξ is depth x, scaled by the extrapolated range, $\xi = x / R_P(E)$. The values of the parameters were obtained by fitting to the experimental data (Fig. 3). The function $P(\xi)$ is normalized, i.e. $\int_0^\infty P(\xi)d\xi = 1$. One can calculate the electron range in aluminum $R_{Al}(E)$ by using Eq. (4). For other materials, having an atomic number Z and an atomic mass A, the electron range can be found in [2] or it can be evaluated using the following scaling law

$$R_P(E) = 0.482 \left(A/Z\right) R_{Al}(E). \qquad (6)$$

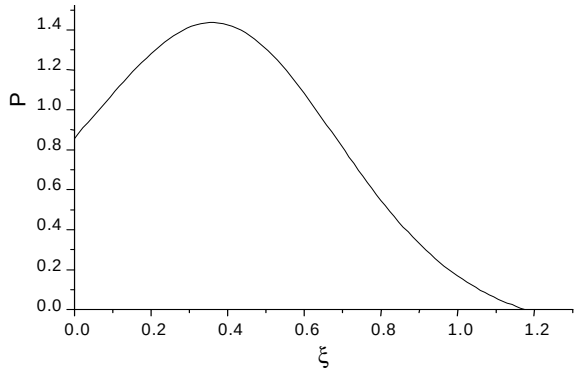

Figure 4. The universal profile of energy deposition.

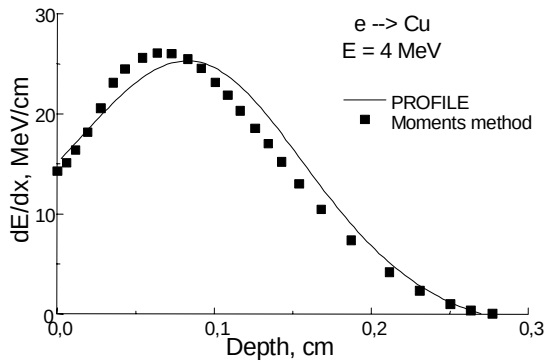

Figure 5. The energy deposition profile in Cu.

So, the energy deposition profile for E MeV-energy electrons can be expressed as

$$Q(x) = \frac{E}{R_P(E)} P\left(\frac{x}{R_P(E)}\right). \qquad (7)$$

The comparison of the profiles, calculated by Eqs. (4-7) (labeled as PROFILE), with the theoretical results, obtained by the moment's series method for copper [9], is shown in Fig. 5.

Calculation of the average absorbed dose

Having the energy deposition profile $Q(x)$, we can calculate the average energy deposition Q_{av} for the sample of given thickness t:

$$Q_{av}(t) = \frac{1}{t}\int_0^t Q(x')dx' \qquad (8)$$

The dependence of Q_{av} on the sample thickness t for NaCl irradiated with 0.5 MeV electrons is shown in Fig. 6.

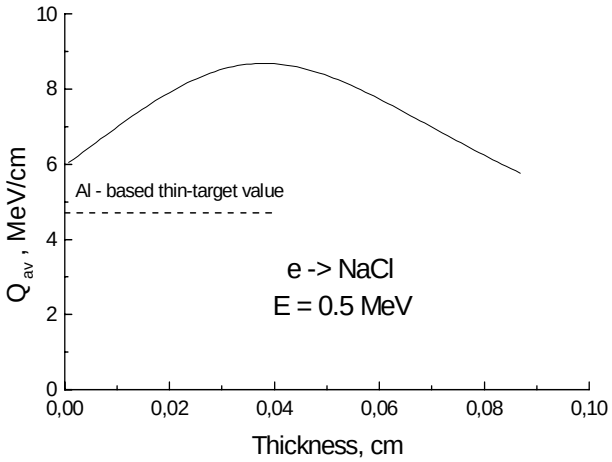

Figure 6. The average deposition profile with and without taking in to account the effect of the back scattering and multi-scattering electrons.

The average value of the deposited energy is plotted in Fig. 6 together with energy loss, calculated with the Bethe-Bloch formula (broken line) with I = 175.3 eV (Seltzer-Berger [2]). By taking into account the build-up of the energy deposition due to back scattering and multi-scattering of electrons, the dose increases by ~100%.

COMPARISON OF EXPERIMENTAL AND THEORETICAL RESULTS

Experimental investigations of the energy deposition profiles in NaCl platelets under E=0.5 MeV electron irradiation have been performed. A set of synthetic NaCl samples with different values for the thickness were irradiated by the Groningen electron accelerator at 100°C up to Seltzer-Berger dose of $D_{S\text{-}B}$= 26 Grad. The depth distribution of the absorbed dose was determined by measuring the stored energy associated with radiation damage, which was created in NaCl during electron irradiation.

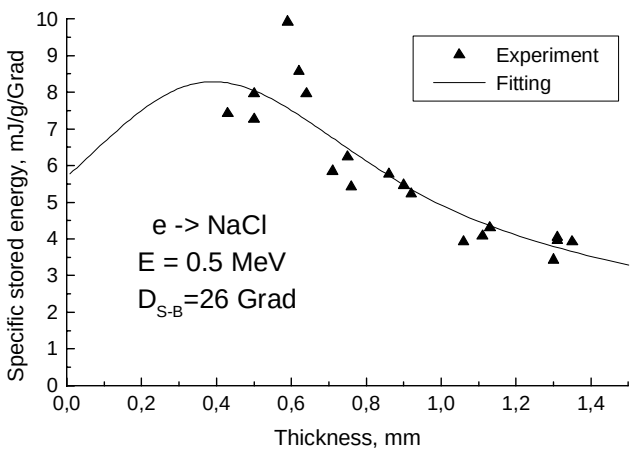

Fig.7. The average specific stored energy vs. the sample thickness.

The stored energy was determined for each sample, using differential scanning calorimetry (DSC), by measuring the latent heat of melting of the radiation-induced Na-precipitates [10]. The experimental results are plotted in Fig.7 together with the predicted average stored energy profile.

The average specific stored energy $W(t)$ is assumed to be proportional to the average absorbed dose:

$$W(t) = \frac{CD_{S-B}}{S\,t}\int_0^t Q(x')dx'. \qquad (9)$$

Here S =4.7 MeV/cm for an electron with energy E = 0.5 MeV, ρ is the density of the sample, C is a proportionality factor, which has been obtained by fitting: C= 4.2 mJ/g/Grad.

The comparison of the experimental data with the calculated profile has shown that the proposed method can serve as a basis for the evaluation of the absorbed dose in alkali halides under electron irradiation in the MeV-energy range.

DISCUSSION

In the past, a point of concern has been the question regarding the dose rate produced by the electron beam. Until now we have employed the method published by Berger and Seltzer, which is used extensively in the present literature. We have concluded that this method does not account for eventual effects associated with the build-up phenomenon, in particular, in the presence of the Al-target plate in which the samples are accommodated. These effects lead to deviations in the dose rate from the Berger and Seltzer values. In this paper we have designed a new model for the calculation of the dose rate in which the secondary effects are included.

Acknowledgement

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