INVESTIGATION OF THE ENERGY DEPOSITION PROFILE IN NaCl UNDER ELECTRON IRRADIATION

V.V. Gann
National Science Center "Kharkov Institute of Physics and Technology",
1, Akademicheskaya st., 61108, Kharkov, Ukraine; E-mail: gann@kipt.kharkov.ua;
H.W. den Hartog, D.I. Vainshtein
University of Groningen, Nijenborgh 4, NL-9747 AG Groningen, The Netherlands;
E-mail: D.Vainshtein@phys.rug.nl

We have proposed a new model for the calculation of the absorbed dose profile in a thick target under 0.1…3 MeV electron irradiation. The build-up phenomenon is shown to increase the maximum of the energy deposition profile in thick samples by a factor of two in comparison with thin targets as a result of backscattered and multi-scattered electrons. The absorbed dose profile in NaCl for 0.5 MeV electron irradiation has been determined by measuring the stored energy with differential scanning calorimetry.

PACS: 61.80.Fe, 81.40.Wx

1. INTRODUCTION

It is necessary to 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 absorbed by the sample at a given depth. The energy losses of monoenergetic electrons due to ionization and excitation processes in thin targets can be described with the Bethe-Bloch formula [1]. The energy loss tables, including the density correction δ and experimentally derived values of mean excitation energy *I,* were published by Seltzer and Berger [2] (for NaCl, the recommended value 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 the 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. Many calculations have been carried out in the literature using the Monte-Carlo method [8] for modeling the motion of high energy electrons in matter.

2. ENERGY LOSS PROFILE

The most complete calculations of the dissipation of energy of perpendicular electron beams in matter have been made by Spencer [3]. Rao [4] derived a simple formula for the fraction of 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 on the sample thickness t, calculated on Eq.1 for a 0.5 MeV electron beam in NaCl is displayed in Fig.1.

The point at which the extrapolation of the linear region meets x-axis is defined as the *practical* (or *extrapolated*) *range* R_P, whereas the point were the tail meets x-axis is known as the *maximum range* R_0 (the background is neglected).

The energy loss profile of a perpendicular incident electron beam can be calculated as proposed in [5]:

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

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

3. RANGE-ENERGY RELATION

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

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

here $\left(\frac{dE'}{dx}\right)_{tot}$ is the value of the total energy losses for an electron with energy E'. R_0 is the total path length traveled to rest. Extended tables of CSDA ranges of electrons in many materials and compounds were published by Seltzer and Berger [2]. Katz and Penfold [6] 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.

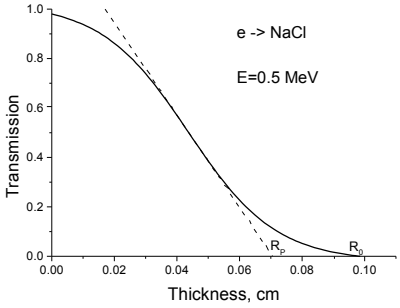

Fig.1. Dependence of beam transmission on the thickness of NaCl samples

4. ENERGY DEPOSITION PROFILE

Some experimentally observed energy deposition profiles for aluminum are shown in Fig.2 [7]. The ener-

gy deposition profiles as well as the energy loss profiles show a pronounced maximum.

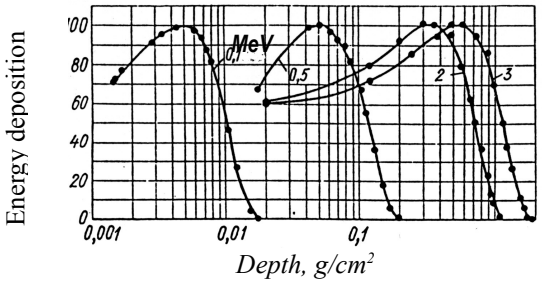

Fig.2. Energy deposition profiles in aluminum, taken from [7]

The 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. The Monte Carlo simulation method is used for the evaluation of the energy deposition profile in 3D-geometry. But the Monte Carlo calculations are very time consuming. 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.

5. UNIVERSAL PROFILE APPROXIMATION

It is seen from Fig. 2 that in the 100 keV…3 MeV energy region, the energy deposition profile $Q(x)$ can be easily scaled in x by the value of practical range $R_P(E)$ and expressed in terms of the universal function $P(\xi)$ (see Fig.3)

$$P(\xi) = \frac{1.065}{\{ch[0.95(2.295\xi - 1)]\}^{1.8}[0.5 + 1/(2.7 - 2.295\xi)]} \qquad (5)$$

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.2) Function $P(\xi)$ is normalized as $\int_0^\infty P(\xi)d\xi = 1$. 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 can be evaluated using the following scaling law

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

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 experimental data for water [7] and with some theoretical results, obtained by the moment's series method for copper [8], is shown in Fig.4 and 5, respectively.

6. 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:

$$Q_{av}(t) = \frac{1}{t}\int_0^t Q(x')dx'. \qquad (7)$$

The dependence of Q_{av} on the sample thickness t for

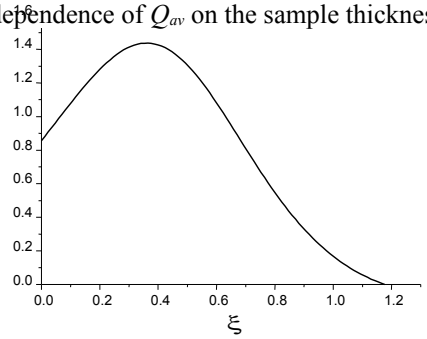

Fig.3. The universal profile of energy deposition

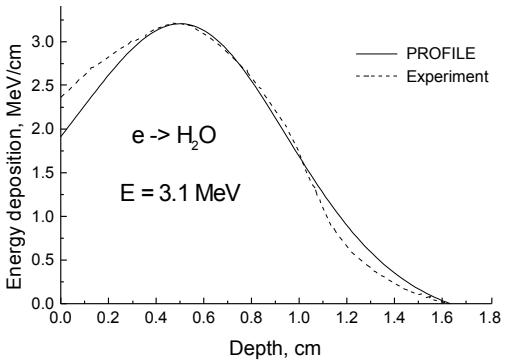

Fig.4. The energy deposition profiles in H_2O

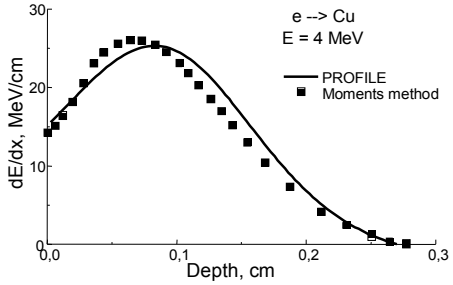

Fig.5. The energy deposition profile in Cu

NaCl irradiated with 0.5 MeV electrons is shown in Fig.6.

The average values of the deposited energy are plotted in Fig.6 together with energy losses, calculated using the Bethe-Bloch formula (broken line) with I=175.3 eV (as proposed by Seltzer-Berger).

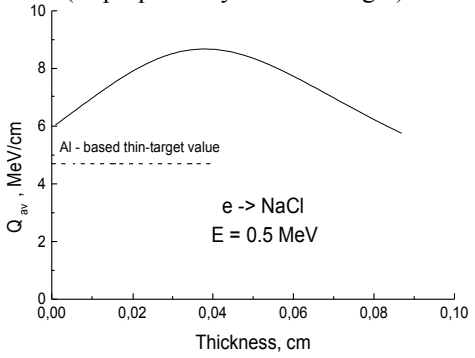

Fig.6. The average deposition profile with and without taking in to account the effect of the back scattering and multi-scattering electrons

One can see that taking into account the build-up of the energy deposition due to back scattering and multi-scattering of electrons results in an increase of the irradiation doses of approximately 100 %.

7. COMPARISON OF THE EXPERIMENTAL AND THEORETICAL RESULTS

Experimental investigations of the energy deposition profiles in NaCl platelets under 0.5 MeV electron irradiation have been performed. A set of NaCl samples, doped with 0.1 mol% K with different values for the thickness were irradiated by the Groningen electron accelerator at 100°C up to a fluence of n=0.63 C/cm^2. 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. The stored energy was measured for each sample, using differential scanning calorimetry (DSC). The experimental results are plotted in Fig.7 together with the predicted average stored energy profile.

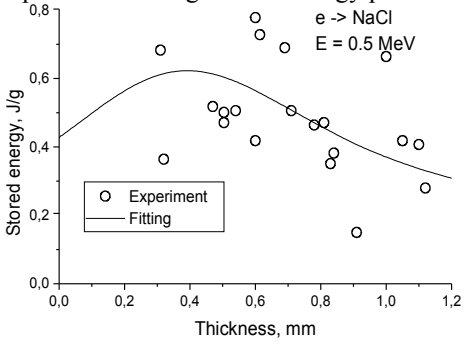

Fig.7. The average stored energy vs. the sample thickness

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

$$W(t) = \frac{Cn}{t\rho}\int_0^t Q(x')dx'. \qquad (8)$$

Here n is the electron fluence, ρ is the density of the sample, C is a proportionality factor, which has been obtained by fitting.

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

8. 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

This study is supported by the Dutch Ministry of Economic Affairs.

REFERENCES

1. H.A. Bethe. *Handbuch fur Physik*. Springer Verlag, Berlin, 1933, v. 24/2.
2. M.J. Berger and S. M. Seltzer. *Stopping power for electrons and positrons (ICRU-37).* Washington D.C., 1984.
3. L.V. Spencer. *Natl. Bur. Std. (U.S.). Monograph 1.* 1959.
4. B.N. Shubba Rao // *Nucl. Instr. Methods.* 1966, v. 44, p. 155.
5. E.J. Kobetich and R. Katz // *Phys. Rev*. 1968, v. 170, p. 391.
6. L. Katz and A.S. Penfold // *Rev. Mod. Phys*. 1952, v. 24, p. 28.
7. *Handbuch der Physik*. Springer Verlag, Berlin. 1958, b. 34.
8. A.M.Colchuzhkin, V.V.Ukchaikin. *Introduction into the theory of particle passing through the matter*. M.: "Atomizdat", 1978

ИССЛЕДОВАНИЕ ПРОФИЛЕЙ ПОГЛОЩЕННОЙ ЭНЕРГИИ В КРИСТАЛЛАХ NaCl ПРИ ЭЛЕКТРОННОМ ОБЛУЧЕНИИ

В.В. Ганн, Г.В. ден Хартог, Д.И. Вайнштейн

Предложена новая модель для расчета профилей поглощенной энергии в толстых мишенях, облучаемых пучком электронов с энергиями 0.1…3 МэВ. Показано, что вследствие эффекта накопления дозы, связанного с многократным и обратным рассеянием электронов, максимальное значение поглощенной энергии в толстых мишенях увеличивается вдвое по сравнению с тонкими мишенями. Изучен профиль распределения поглощенной энергии в кристаллической пластинке NaCl, облученной электронами с энергией 0.5 МэВ, путем измерения запасенной энергии методом дифференциальной сканирующей калориметрии.

ДОСЛІДЖЕННЯ ПРОФІЛІВ ПОГЛИНЕНОЇ ЕНЕРГІЇ В КРИСТАЛАХ NaCl ПРИ ЕЛЕКТРОННОМУ ОПРОМІНЕННІ

В.В. Ганн, Г.В. ден Хартог, Д.І. Вайнштейн

Запропоновано нову модель для розрахунку профілів поглиненої енергії в товстих мішенях, що опромінюються пучком електронів з енергіями 0.1…3 МеВ. Показано, що внаслідок ефекту накопичування

дози, зв'язаного з багаторазовим і зворотним розсіюванням електронів, максимальне значення поглиненої енергії у товстих мішенях збільшується вдвічі в порівнянні з тонкими мішенями. Вивчено профіль розподілу поглиненої енергії в кристалічній пластинці NaCl, опроміненої електронами з енергією 0.5 МеВ, шляхом вимірювання запасеної енергії методом диференціальної скануємої калориметрії.