Conference Paper

The Light Nuclei Stopping in a Solid

B. Yu. Bogdanovich, A. V. Nesterovich, and A. E. Shikanov

National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe shosse 31, Moscow, 115409, Russia

Abstract

The report discusses processes of light nuclei stopping in a solid-state barrier. Accounting algorithm of energy losses of light nuclei for (0 ÷ 20) MeV – range was considered. Calculated functions of the energy losses for various materials were presented.

Corresponding Author:
A. E. Shikanov
aeshikanov14@mail.ru

Received: 22 July 2018
Accepted: 9 September 2018
Published: 8 October 2018

Publishing services provided by Knowledge E

© B. Yu. Bogdanovich et al. This article is distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use and redistribution provided that the original author and source are credited.

Selection and Peer-review under the responsibility of the Breakthrough Directions of Scientific Research at MEPhI Conference Committee.

OPEN ACCESS

1. Introduction

In this article, the authors focus on the process of bombarding the surface of a solid-state barrier with light nuclei with energies up to 20 MeV, which are the products of fusion reactions. According to the considerations given in [1], in order to estimate the energy losses of nuclei in the surface layer of a solid in the region of kinetic energies of the nuclei satisfying condition

$$T >> 10^{-6}\frac{e^3 M}{2h^2\varepsilon_0^2} Z_1^2 A_1 \cong 0.1 Z_1^2 A_1 \text{ [MeV]},$$

the formula Bethe–Bloch can be used:

$$F_+(w) = -\frac{dT}{dx} = 10^{-6}\frac{2\pi e^3 M}{m}\frac{\rho Z_1^2 Z_2}{A_2 w}\ln[10^6\frac{4m}{M}\frac{w}{I(Z_2)}] \text{ [MeV/m]}, \quad (1)$$

where $w = \frac{T}{A_1}$ – the kinetic energy per nucleon in the stopping nucleus (reduced kinetic energy), e – the elementary charge, M – the mass of a proton, m – the mass of an electron, A_1, Z_1 – the atomic masses and numbers of the stopping nuclei, A_2, Z_2, ρ, – the atomic numbers and the density of a stopping substance, respectively, $I(Z) \cong 10(Z + 0,5)$-[V] – the mean ionization potential [2].

The guaranteed lower limit for the applicability of the Bethe–Bloch formula in this case is several MeV.

The purpose of this report is to obtain accounting algorithm of energy losses of light nuclei for (0 ÷ 20) MeV – range.

How to cite this article: B. Yu. Bogdanovich, A. V. Nesterovich, and A. E. Shikanov, (2018), "The Light Nuclei Stopping in a Solid" in *MEPhI's Section of the Scientific Session on "Breakthrough directions of scientific research at MEPhI: Development prospects within the Strategic Academic Units"*, KnE Engineering, pages 85–89. DOI 10.18502/keg.v3i6.2976

2. Accounting Algorithm

At lower kinetic energies, one can use the empirical formula obtained on the basis of the data from [3], which gives a good approximation to the function of the energy losses in the energy range of (0 ÷ 5):

$$F_{-}(w) = 10^{-6}\alpha\frac{\rho Z_1^2 Z_2 w^{0.5}}{A_2}\frac{1+\beta w^{0.5}}{w^{1.275}+\gamma}. \tag{2}$$

The parameters in formula (2) for some possible elements are determined in the following table.

Table 1: Parameters in formula (2).

Element	Be	C	Al	Ti	Fe	Cu	Zr
α	50.2	62.15	31.55	28.10	32.00	26.80	17.00
β	0.006	0.085	0.104	0.110	0.020	1.124	0.063
γ	0.046	0.049	0.044	0.038	0.123	0.103	0.041

For computer modeling of the processes of the nuclei stopping in a solid, it is necessary to specify a continuous function of the energy losses in the entire energy range of $[0 \div w_{max}]$, where w_{max} is the maximum value of reduced kinetic energy in the spectrum of the stopping nuclei. This requires matching expressions (1) and (2). In the simplest case, this can be done by linear interpolation using the function

$$\tilde{F}(w) = a_0 - a_1 w, \tag{3}$$

where $a_1 = \frac{F_{-}(w_c-\delta)-F_{+}(w_c+\delta)}{2\delta}$

$$a_0 = \frac{(w_c+\delta)F_{-}(w_c-\delta)-(w_c-\delta)F_{+}(w_c+\delta)}{2\delta}.$$

The value w_c is determined by the intersection of the curves $F_{-}(w)$ and $F_{+}(w)$; δ – the arbitrary parameter selected in the range of [0.1 ÷ 1] MeV. As a result of such constructions, a continuous, sufficiently smooth function of energy losses is obtained

$$F(w) = \begin{cases} F_{-}(w), 0 < w < w_c - \delta \\ \tilde{F}(w), w_c - \delta < w < w_c + \delta \\ F_{+}(w), w_c + \delta < w < w_{\max} \end{cases}. \tag{4}$$

The degree of its smoothness can be improved by using in the proposed matching procedure a cubic spline

$$\tilde{F}(w) = \sum_{n=0}^{3} a_n (w-\delta)^n$$

DOI 10.18502/keg.v3i6.2976

instead of a linear function (2). Vector $a = \{a_0, a_1, a_2, a_3\}$is the solution of next linear algebraic equation:

$$a\left\Vert\begin{matrix} 1 & 0 & 1 & 0 \\ w_0-\delta & 1 & w_0+\delta & 1 \\ (w_0-\delta)^2 & 2(w_0-\delta) & (w_0+\delta)^2 & 2(w_0+\delta) \\ (w_0-\delta)^3 & 3(w_0-\delta)^2 & (w_0+\delta)^3 & 3(w_0+\delta)^3 \end{matrix}\right\Vert$$

$$= \left\Vert\begin{matrix} F_-(w_0-\delta) & F_-^{'}(w_0-\delta) & F_+(w_0+\delta) & F_+(w_0+\delta) \end{matrix}\right\Vert.$$

3. The Calculated Results

Figure 1 presents the calculated functions of the energy losses obtained on the basis of the described algorithm for various materials.

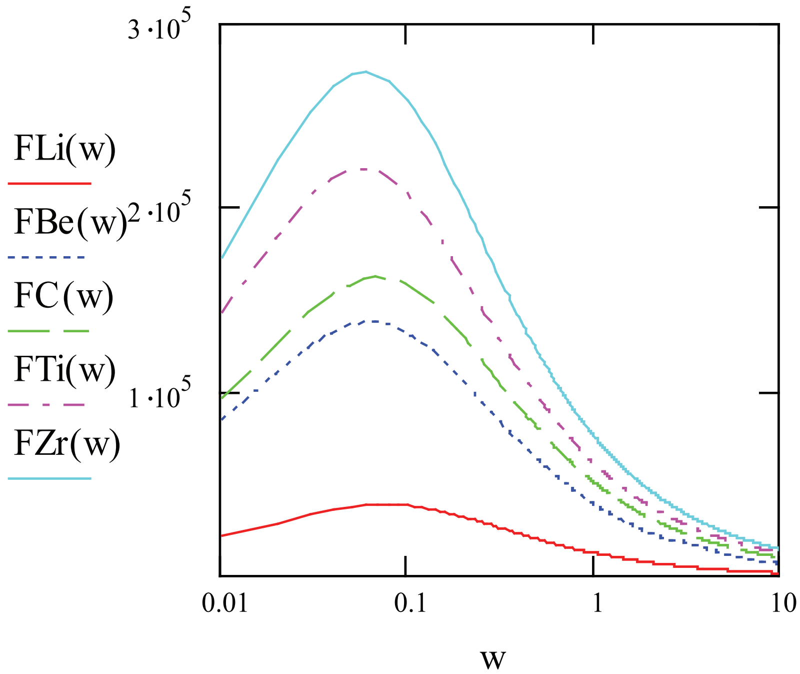

Figure 1: The calculated dependences of the energy losses of a nucleus moving in zirconium (the upper curve), in titanium (the second curve from above), in carbon (the third from above), in beryllium and lithium (the lower curve).

Figure 2 shows the characteristic calculated dependences of the kinetic energy of the nucleus per nucleon from the depth of its penetration into a solid.

These curves were obtained by were obtained by the numerical solution of a differential equation

$$\frac{dw}{dx} = -\frac{F(w)}{A_1}$$

DOI 10.18502/keg.v3i6.2976

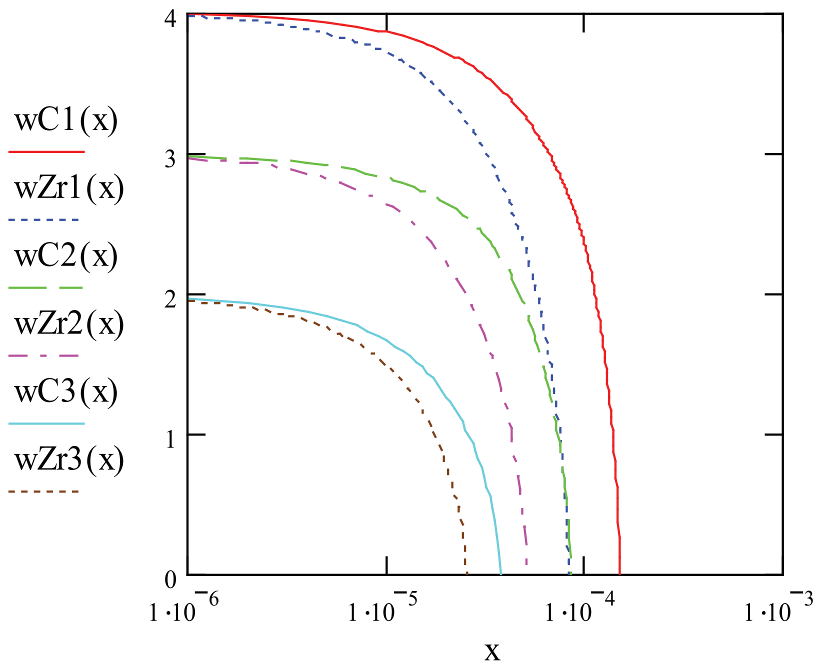

Figure 2: Three pairs of calculated dependences of the kinetic energy of the nucleus per nucleon from the depth of penetration into carbon (upper curves in pairs) and zirconium. The pair of curves *wC*1(*x*) and *wZr*1(*x*) corresponds to the initial energy w_0 = 4MeV; the pair *wC*2(*x*), *wZr*2(*x*) to w_0 = 3MeV; the pair *wC*3(*x*), *wZr*3(*x*) to w_0 = 2MeV.

with initial conditions $w(0) = \{4; 3; 2\}$ MeV.

The path length of the nucleus will be the root of the equation w (x) = 0 and can be estimated for the case in question directly from Figure 2.

4. Case of Multiply Component Barrier

The elaborated algorithm can be generalized to the case when a solid under consideration represents a composition of *N* different elements with stoichiometry coefficients k_n normalized to 1 ($\sum_{n=1}^{N} k_n = 1$). In this case, according to the principle of additivity, the loss function can be represented as the sum:

$$F(w) = \sum_{n=1}^{N} k_n F_n(w),$$

where the partial loss functions corresponding to different stopping components are calculated by formulas (1–3), in which the values of A_2, Z_2 are replaced by the corresponding values for various components. Similarly, the coefficients α, β, γ should be replaced according to their table values.

Thus, the algorithm has been developed for calculating the functions of energy losses in solids based on the interpolation matching of the empirical formula for the energy losses in the low-energy region with the analytical Bethe–Bloch formula, which accurately describes the stopping in the medium-energy region. The proposed analytical formulae make it possible to increase the accuracy and reliability of calculations of heat at stopping the nuclei in solids, and can also be used in calculating the output parameters of the projected neutron generators.

5. Conclusion

1. Accounting algorithm of energy losses of light nuclei for (0 ÷ 20) MeV – range was considered.
2. Calculated functions of the energy losses for various materials were presented.

Funding

The work was performed as a part of the [Grant Agreement # 15-19-00151] between the Russian Science Foundation, 'National Research Nuclear University "MEPhI"' and A. B. Nesterovich, Head of the project, to conduct fundamental and pilot studies.

References

[1] Lehmann, C. (1979). *Interaction of Radiation with Solids and Elementary Defect Production*, p. 296. Moscow, Atomizdat (in Russian).

[2] Gusev, N. G., Klimanov, V. A., Mashkovich, V. P., et al. (1989). Protection from ionizing radiation. *Physical Fundamentals of Radiation Protection*, vol. 1, p. 514. Moscow, Energoatomizdat (in Russian).

[3] Gott, Yu. V. (1978). *Interaction of Particles with Substances in Plasma Research*, p. 272. Moscow, Atomizdat (in Russian).