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Mean excitation energies extracted from stopping power measurements of protons in polymers by using the modified Bethe–Bloch formula

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Abstract

Recent stopping power measurements in thin polymeric films have been performed for protons of 0.4–3.5 MeV energies using the indirect transmission technique [H. Ammi, S. Mammeri, M. Chekirine, B. Bouzid, M. Allab, Nucl. Instr. and Meth. B 198 (2002) 5]. Experimental stopping data have been analyzed with the modified Bethe–Bloch formula and the mean excitation energies I have been then extracted from the data. Resulting values for each thin film are 76 ± 1 eV in Mylar, 70.8 ± 1 eV in Makrofol, 82.2 ± 1.2 eV in LR-115 and 55.4 ± 1 eV in Polypropylene. The I-extracted values are compared to those I_B calculated by using the Bragg's rule.

Keywords: Stopping power; Mean excitation energy; Modified Bethe–Bloch theory

1. Introduction

The stopping power of ions in matter have been considered theoretically since the early days of atomic physics starting with Bohr, Thomson and Rutherford. The interest was first motivated by the necessity to get a good theoretical understanding of the slowing down process in order to extract information about the nature of the studied atomic particles. Furthermore, the analysis of penetration phenomena offered a testing ground for the theoretical treatments being developed, starting with classical methods and subsequently turning to quantum mechanical methods and finally the computer simulation codes which still remain a best tool in the iterative dialogue between theory and experiment.

Accurate stopping power data in variety of materials and energies ranges are of practical importance in a number of contemporary experiments used extensively in materials science, such

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as ion implantation and ion-beam analysis, which require accurate knowledge of stopping power and ranges values. The energy loss per path length called stopping power has been studied and reviewed extensively, both theoretically and experimentally [1–6]. The additivity rule proposed by Bragg and Kleeman [7] for stopping power S_c in compounds, estimated by the linear combination of the stopping power S_i of the individual elements $\left(S_c = \sum_{i=1}^{n} n_i S_i\right)$, was reasonably verified in several compounds submitted to different incident particles at various energies with deviations less than 20%, as reported in previous work by Ziegler and Manoyan [8]. Recent stopping power measurements of light ions (^{1}H, ^{2}H and ^{4}H$_e$ particles) in different polymer films confirm this result with precision better than 5%, at incident energies ranging from 500 keV to 3000 keV [9–11].

In this work, proton stopping power measurements in thin polymeric films performed using the indirect transmission technique, are combined to the theoretical calculation based on the modified Bethe–Bloch formula in order to deduce the mean excitation energy.

1.1. Theoretical approach

The formalism of Bethe–Bloch theory of stopping power, including various modifications, has been described extensively in several investigations [14–19]. The stopping power S of an elemental target of atomic number Z_2 and atomic weight A for a projectile of atomic number Z_1 and velocity v ($v = \beta c$, where c is the light velocity), can be expressed by

$$S(E) = \frac{\kappa Z_1^2 Z_2}{\beta^2}\left\{L_0(\beta) + Z_1 L_1(\beta) + Z_1^2 L_2(\beta)\right\}, \qquad (1)$$

where κ is a constant and L_0 is the main stopping number given by

$$L_0(\beta) = \left\{\ln\left(\frac{2m_e v^2}{\langle I\rangle}\right) - \ln(1-\beta^2) - \beta^2 - \frac{C}{Z_2} + \frac{\delta}{2}\right\}, \qquad (2)$$

whereas $\langle I\rangle$, (C/Z_2) and δ represent, respectively, the mean excitation energy, the sum of the target shell corrections and the density effect correction which is neglected at low energies [20]. $Z_1L_1(\beta)$ is a secondary correction term due to the Barkas effect that can be estimated from the empirical formula developed recently by Ziegler [2]. The third term defined in Eq. (1), $Z_1^2L_2(\beta)$, called the Bloch correction, has a small contribution to the stopping power number [2] in the investigated energy range.

To extract the $\langle I\rangle$ value, a modification of Bichsel's X variable [21] is used. The X_{exp} and X_{theo} variables are defined as

$$X_{\text{exp}} = \ln\left(\frac{2m_e v^2}{1-\beta^2}\right) - \beta^2 - \frac{\beta^2 S_{\text{exp}}(E)}{\kappa Z_1^2 Z_2}, \qquad (3)$$

$$X_{\text{theo}} = \ln\langle I\rangle + \frac{C}{Z_2} + \frac{\delta}{2} - Z_1 L_1 - Z_1^2 L_2, \qquad (4)$$

where S_{exp} is the obtained experimental stopping power.

For compounds materials, we assume the following replacement in Eq. (1) as proposed by [22,23]:

$$\langle F\rangle \equiv \langle Z_2/A\rangle_C^{-1}\sum_i \frac{w_i Z_{2i}}{A_i} F_i, \qquad (5)$$

with $\langle Z_2/A\rangle_C^{-1} = \sum_i w_i \frac{Z_{2i}}{A_i}$, where Z_{2i}, A_i and w_i are, respectively, the atomic number, the weight and the concentration of the ith component of the composite target material. F_i and $\langle F\rangle$ are, respectively, the ith component of the considered parameters (mean excitation energy I_i or shell corrections $(C/Z_2)_i$) and the corresponding parameters of composite material.

A test of linear additivity rule [7] is generally confined to the comparison between the measured values of the mean excitation energy $\langle I\rangle_C$ and the calculated $\langle I_B\rangle$ using the Bragg's rule as model of calculation (Eq. (5)) [22,23].

2. Results and discussion

2.1. Stopping power data

The experimental method used in this work to perform stopping power measurements has been described previously in our published papers [12,13]. Thus, only the results of the stopping power analysis are reported in the present study. In Fig. 1, we report the experimental stopping power values of each compound in the whole investigated energy range. The obtained stopping power data agree well with those calculated by ZBL model [24] and those given in ICRU (49) report [25]. It denotes the good accuracy of the improved experimental technique used in this work and point out the good applicability of Bragg's law in stopping power measurements.

2.2. Mean excitation energy

The shell correction parameter (C/Z_2) for composite materials, was calculated by inverting the Bethe–Bloch equation, as

$$\left(\frac{C}{Z_2}\right) = f(\beta) - \ln\langle I\rangle_{\text{theo}} - \frac{\beta^2 S_{\text{calc}}}{kZ_2Z_1^2} + Z_1L_1 + Z_1^2L_2, \tag{6}$$

where $\langle I\rangle_{\text{theo}}$ (eV) = $11.4 \times Z_2$ is a simple empirical relation of the mean ionization potential [2] and S_{calc} is the stopping power values generated by the SRIM simulation code.

X_{exp} is determined by the obtained experimental values of stopping power including the average atomic number $\overline{Z}_2$ and the average atomic weight $\overline{A}$. The value of the mean excitation energy for composite materials $\langle I\rangle_C$ was taken as an adjustable parameter and determined from X_{theo} by the least squares fit of the X_{exp}. The best fit of the experimental data are shown in Fig. 2 for Mylar, Makrofol, Polypropylene and LR115 targets. The obtained $\langle I\rangle_C$-values compared to those given by ICRU report 49 and the corresponding ones calculated by using the Bragg's additivity rule are displayed in Table 1. The obtained values for each thin film are in good agreement with those calculated by Bragg's rule. For Mylar film, our extracted I-value agrees well with those given by Hiraoka et al. [26] (75.3 ± 4 eV). However, those reported by Shiomi-Tsuda [27] (80.2 ± 1.7 eV) exceed our data by few percent 5%. No available experimental data have been found in the literature, especially for Makrofol, Polypropylene and

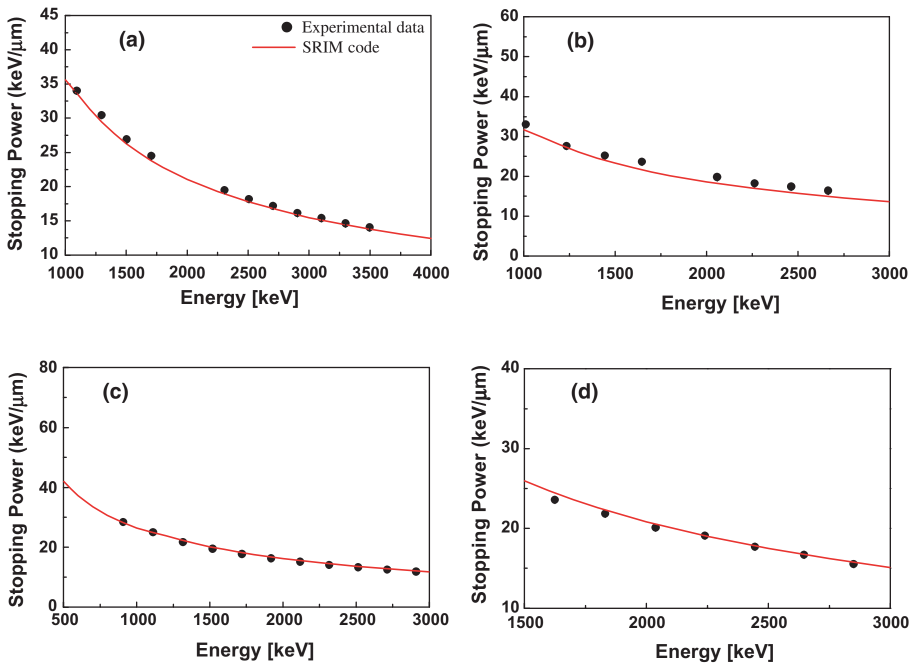

Fig. 1. Experimental stopping power of protons in (a) Mylar, (b) Makrofol, (c) Polypropylene and (d) LR-115, compared to the theoretical values deduced from SRIM code.

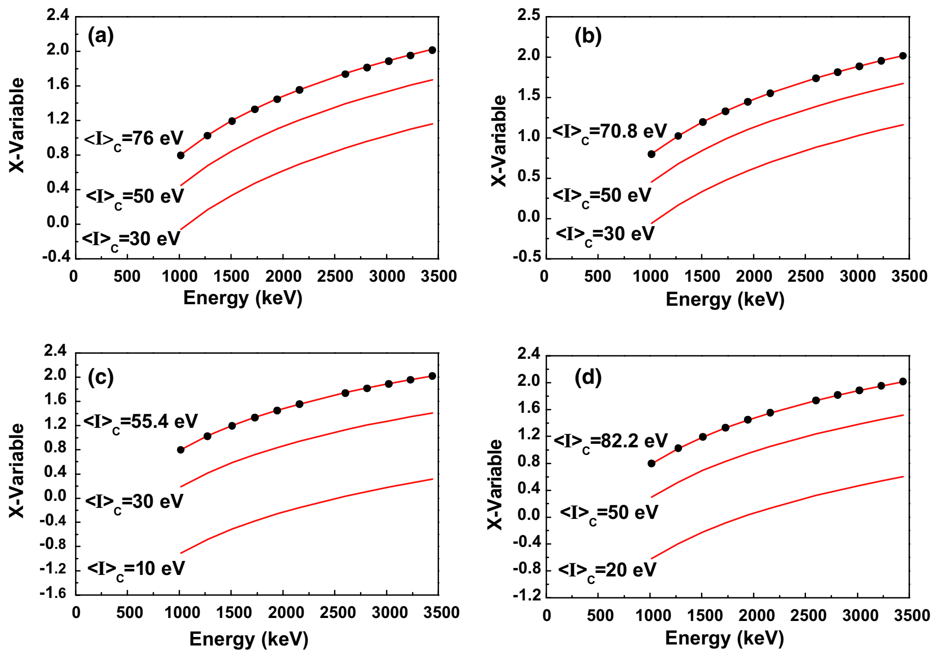

Fig. 2. X_{exp} and X_{theo} curves with the best fit $\langle I \rangle_C$ values for (a) Mylar, (b) Makrofol, (c) polypropylene and (d) LR-115. The X-parameter in the text.

Table 1
The present $\langle I \rangle$ values compared to Bragg values I_B

Composite material	I_{exp} (eV)	I_B (eV)
Mylar	76 ± 1.1	75.7
Makrofol	70.8 ± 1.1	70.9
Polypropylene	55.4 ± 1	55.3
LR 115	82.2 ± 1.2	81.8

LR 115, to make possible a comparison to the present extracted values. Our experimental results point out the good applicability of Bragg's law in the calculation of the mean excitation energy for composite material.

3. Conclusion

The indirect transmission technique reported previously [12,13] has been used to determine the mean excitation energy in thin polymeric foils. Experimental stopping power values for proton in the energy range from 500 to 3000 keV have been obtained and analyzed in terms of the modified Bethe–Bloch theory. The mean excitation energy for each polymeric foils have been extracted from the stopping power data. The obtained results are 76 ± 1 eV for Mylar, 70.8 ± 1 eV for Makrofol, 55.4 ± 1 eV for Polypropylene and 82.2 ± 1.2 eV for LR-115. These values are in good agreement with the recommended ones of ICRU 49. The Bragg's law has thus been tested successfully in slowing down experiments in order to extract I-parameter.

References

[1] P. Sigmund, Nucl. Instr. and Meth. B 135 (1998) 1.
[2] J.F. Ziegler, J. Appl. Phys. 85 (1999) 1249.
[3] J. Räisänen, U. Watjen, A.J.M. Plompen, F. Munnik, Nucl. Instr. and Meth. B 118 (1996) 1.
[4] L. Leblanc, G.G. Ross, W.E. Wallace, Nucl. Instr. and Meth. B 95 (1995) 457.
[5] A. Climent-Font, J. Räisänen, E. Rauhala, Nucl. Instr. and Meth. B 136–138 (1998) 109.
[6] R. Liguori, N. Added, F.A.S. Coutinho, Nucl. Instr. and Meth. B 161–163 (2000) 159.
[7] W.H. Bragg, R. Kleean, Philos. Mag 10 (1905) 318.

[8] J.F Ziegler, J. Manoyan, Nucl. Instr. and Meth. B 35 (1988) 215.
[9] H. Ammi, M. Chekirine, A. Adjerad, Radiat. Meas. 28 (1997) 1.
[10] M. Chekirine, H. Ammi, M. Allab, Radiat. Meas. 30 (1999) 131.
[11] H. Ammi, M. Chekirine, M. Allab, Radiat. Meas. 32 (2000) 83.
[12] H. Ammi, S. Memmeri, M. Chekirine, B. Bouzid, M. Allab, Nucl. Instr. and Meth. B 198 (2002) 5.
[13] H. Ammi, S. Memmeri, M. Allab, Nucl. Instr. and Meth. B 213 (2004) 60.
[14] L.E. Porter, E. Rauhala, J. Raisanen, Phys. Rev. B 49 (1994) 11543.
[15] L.E. Porter, Appl. Phys. Lett. 61 (3) (1992) 360.
[16] L.E. Porter, Phys. Rev. A50 (1994) 2397.
[17] L.E. Porter, Nucl. Instr. and Meth. B 149 (1999) 373.
[18] L.E. Porter, Int. J. Quantum Chem. 75 (4/5) (1999).
[19] L.E. Porter, Int. J. Quantum Chem. 65 (1997) 997.
[20] R.M. Sternheimer, M.J. Berger, S.M. Seltzer, At. Data Nucl. Data tables 30 (1984) 261.
[21] H. Bichsel, in: U. Fano (Ed.), Studies in Penetration of Charged Particles in Matter, NAS-NRC Publ. 1133, 1964, p. 17.
[22] U. Fano, Ann. Rev. Nucl. Sci. 13 (1963) 1.
[23] W.H. Barkas, M.J. Berger, Studies in Penetration of Charged Particles in Matter, National Academy of Sciences-National Research Council Publication No. 1133, NAS-NRC, Washington, DC, 1967.
[24] J.F. Ziegler, J.P. Biersack, U. Littmark, The Stopping and Ranges of Ions in Solids, Vol. 1, Pergamon Press, New York, 1985.
[25] ICRU report 49, International commission on radiation units and measurements, ICRU publications, Bethesda, Maryland, 1993.
[26] T. Hiraoka, K. Hawashia, K. Hoshino, A. Fukumura, H. Bichsel, Med. Phys. 20 (1993) 135.
[27] N. Shiomi-Tsuda, N. Sakamoto, H. Ogawa, Nucl. Instr. and Meth. B 103 (1995) 255.