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The stopping powers and energy straggling of heavy ions in polymer foils

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ABSTRACT

The stopping power and energy straggling of ^{7}Li, ^{12}C and ^{16}O ions in thin poly(etheretherketone) (PEEK), polyethylene terephthalate (PET) and polycarbonate (PC) foils were measured in the incident beam energy range of 9.4–11.8 MeV using an indirect transmission method. Ions scattered from a thin gold target at an angle of 150° were registered by a partially depleted PIPS detector, partly shielded with a polymer foil placed in front of the detector. Therefore, the signals from both direct and slowed down ions were visible in the same energy spectrum, which was evaluated by the ITAP code, developed at our laboratory. The ITAP code was employed to perform a Gaussian-fitting procedure to provide a complete analysis of each measured spectrum. The measured stopping powers were compared with the predictions obtained from the SRIM-2008 and MSTAR codes and with previous experimental data. The energy straggling data were compared with those calculated by using Bohr's, Lindhard–Scharff and Bethe–Livingston theories.

1. Introduction

When energetic ions penetrate the matter, the statistical nature of the collision process involved leads not only to an energy loss but also to an energy broadening of the ion beam, known as energy straggling [1]. The knowledge of both the energy loss and the energy straggling is important for the application of ion beams in material analyses and material modification by ion implantation, for ionising radiation dosimetry and for tumour treatment in medicine. Experimental stopping power and straggling data are also needed for the validation of theoretical and semi-empirical models. For these reasons, ion energy loss and energy straggling in various materials have been the subject of extensive investigations over the past decades [2–10]. Although the stopping power data for elemental targets are available in the literature, the data for complex materials like polymers are quite limited. Also the experimental data on the stopping powers of heavier ions are rather scarce. The results of such measurements might be used to modify the reference data sets of SRIM-2008 [11] and related codes.

In the present study, the stopping power and energy straggling of 9.4–11.8 MeV Li, C and O ions in polycarbonate (PC), poly(etheretherketone) (PEEK) and polyethylene terephthalate (PET) were measured. The experimental data could provide useful information for further studies of the energy loss of ions in compounds. The measured stopping powers were compared with the calculated values obtained by two different semi-empirical models, Bragg's rule [12,13] and the cores-and-bonds model. Bragg's rule calculates the stopping power of compound targets S_c as the weighted average of pure elemental target stopping powers. The accuracy of Bragg's rule is limited. This rule sometimes implies uncertainties higher than 10%; they can reach 20% around the stopping maximum for light organic gases and for solid compounds containing heavier constituents, such as oxides and nitrides [14].

The cores-and-bonds (CAB) model estimates the stopping power for compounds from the measured values compiled in an empirical database [11]. In this model, each organic molecule in a polymer matrix is described as a set of atomic cores and bonds, corresponding to the nonbonding core and bonding valence electrons, respectively. The CAB model becomes less accurate when the significant effect of the physical state of the investigated materials is expected, which is not our case, we are not studying gaseous targets or targets containing heavier constituents. As an indication, it has been observed in previous experiments that for light ions values of stopping powers are up to 20% larger in vapour than in the solid phase, whereas for heavier ions the opposite has been reported, that is, values of the stopping powers are then up to 20% lower in gases than in solids [14–17]. The program MSTAR [18] was used for stopping power predictions and a model of calculation Bragg's rule is included in this simulation. The CAB model is included in SRIM-2008 computer code.

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2. Experimental details

The experiments were carried out on a Tandetron MC 4130 accelerator at the Nuclear Physics Institute in Rez near Prague. The ion-beam energy was changed by 400-keV steps in the energy range from 9.4 to 11.8 MeV. A transmission technique similar to that used e.g. in [8] was applied. The ion beam back-scattered from a thin gold target was registered by a detector partly covered with a polymer foil. In this way, both signals, from direct and slowed-down ions, are registered simultaneously and systematic errors arising from beam energy instability, foil inhomogeneity, etc. are reduced.

The gold target was prepared by vacuum evaporation of gold onto the glassy carbon substrate. The thickness of the gold layer was verified by the Atomic Force Microscopy analysis (AFM) as 18.7 ± 1.8 nm. The ions scattered from the gold target at a scattering angle of 150° were registered with a partially depleted PIPS detector with an active area of 25 mm^2 and a depletion layer 100 μm thick placed 7 cm away from the target. The detector was covered by an aluminium collimator with two identical holes 2 mm in diameter. One of the holes was covered with the polymer foil. Standard spectrometric system was used for detector signal processing and energy spectra accumulation. The system energy resolution for heavier ions increased rapidly with ion mass. Typical FWHMs (Full Width in Half Maximum) for 5.486 MeV Li, C and O ions were ~35 keV, ~55 keV and ~78 keV, respectively [19]). Evaluation of the measured spectra was performed using the ITAP code, developed in our laboratory. The program, written in FORTRAN 90, uses the Levenberg–Marquardt algorithm for nonlinear least squares Gaussian fit of the peaks corresponding to the direct and slowed down ions.

The present experiment was carried out with PC, PEEK and PET foils, purchased from Goodfellow [20], with respective declared thicknesses of 2.9 μm, 5.4 μm and 2.3 μm. The declared thicknesses were verified by repeated weighing of a foil segment on a microbalance (the details are described in [21]). The mean areal mass densities of the foils were 0.35 ± 0.01, 0.72 ± 0.02 and 0.32 ± 0.01 mg/cm^2 for PC, PEEK and PET, respectively.

3. Results and discussions

3.1. Stopping-power data

A typical energy spectrum of 10.2 MeV C ions and PET foil is shown in Fig. 1. The measured spectrum is compared with the best fit by the ITAP program, which is used to determine the positions and FWHM of both peaks. The experimental values of energy loss ΔE were deduced from the shift in the positions of the peaks corresponding to direct and slowed down ions. The stopping power S of the ions is obtained in common way by dividing the energy loss ΔE by the thickness of the foil Δx [22]:

$$S = \frac{\Delta E}{\Delta x}. \tag{1}$$

Since the ion energy continuously changes during the passage through the foil of a finite thickness, we define reference energy E_{av} as:

$$E_{av} = E_1 - \frac{\Delta E}{2}, \tag{2}$$

where E_1 is the energy of the back-scattered ions coming from the gold target. E_1 is connected with the nominal energy of ions produced E_0 by Tandetron by the expression $E_1 = K \cdot E_0$, where K is the kinematic factor [1].

Typical uncertainties of the measured stopping powers we can divide into two main parts, errors of energy loss ΔE and errors of the foil thickness Δx. The error of energy loss ΔE includes mainly the influence of the energy detector resolution and of the energy shift extraction from the two peak spectrum, which are different comparing the various ions used in our experiment. The errors of the foil thickness Δx include mainly the uncertainty of the foil thickness and were determined from the foil weighting. The error of the foil homogeneity is partially evaluated in the foil thickness uncertainty and we are using very small area of the foil for our experiments, where can be larger effect of the foil inhomogeneity concerning the density changes neglected. The value of the stopping power uncertainties have been estimated finally as 2.5%, 2.8%, 3.4% for Li, C and O in PET, respectively and 2.7%, 3.3% for C and O ions in PC and 3.0% and 3.6% for C and O in PEEK, respectively.

We also determined the influence of uncertainty of E_{av} to the measured stopping powers. By the method used in this work, only an estimate of the stopping power averaged over the energy interval ΔE is determined, which should differ from real values for E_{av} evaluated by the adopting (Eq. (2)). The difference ΔS can roughly be estimated using formula following from common error propagation rule:

$$\Delta S = \frac{dS}{dE} \cdot \frac{\Delta E}{\sqrt{12}}, \tag{3}$$

where dS/dE is an estimate of the slope of S versus E dependence. For ΔE = 2.5 MeV of Fig. 1 and dS/dE = 0.2 estimated from Fig. 2 we obtain ΔS = 0.15 MeV/mg cm^{-2} for C ions in PET. This value may be interpreted as an additional uncertainty in quoted stopping powers and one can see that it is lower than the errors arising from other sources.

The measured stopping-powers in the PET foil for Li, C and O as a function of the ion energy are presented in Fig. 2(a)–(c). The values calculated from the SRIM-2008, MSTAR code and other experimental data taken from Paul's database [23–26] are shown for comparison. The measured stopping powers of Li ions in the energy range E_{av} of 7.8–10.0 MeV in PET are lower than those calculated by the SRIM-2008 code but higher than those calculated by the MSTAR code, the differences being within 1.1–2.4% for SRIM and 0.2–1.2% for MSTAR. The measured stopping powers of C ions in the energy range of 6.2–8.2 MeV in PET are higher than those calculated by the SRIM-2008 code, the differences being within 0.2–2.1%. The values of the measured stopping powers of O ions in PET lie between those calculated by SRIM-2008 and MSTAR codes.

We can see, that Li stopping powers in PET are in a good agreement comparing to the theoretical predictions provided by SRIM and MSTAR, thus there is no significant difference between the

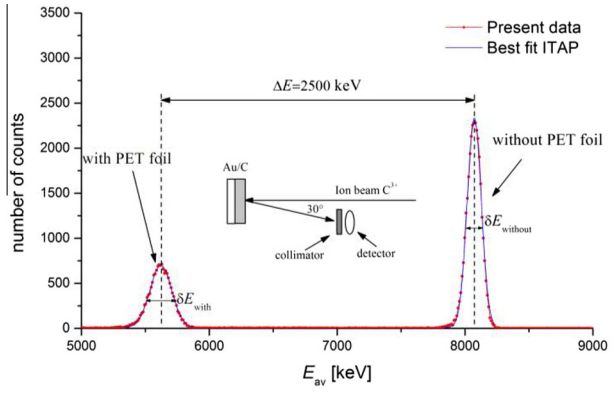

Fig. 1. The experimental spectrum of 10.2 MeV C ions backscattered from the Au/C substrate and penetrating the thin PET foil.