



# Random energy loss and straggling study of Li into Si

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## Abstract

In the present work we have measured the random  ${}^7\text{Li}$  stopping power and range straggling into Si. With this aim we have employed the Rutherford backscattering (RBS) technique together with a multilayer Sb/Si marker. The stopping power measurements were performed in the 280–8500 keV energy interval, while the range straggling ones were done in the 380–2500 keV energy interval. The present results were compared with the TRIM predictions and the semi-empirical calculations by the Kalbitzer group, and an overall good agreement was found for both cases. © 2001 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

The energy loss of light projectiles is an important issue for materials modification by bombarding ions. This is not only because of its direct application in beam analysis but also in order to improve the understanding of fundamental ion–solid interactions. Furthermore, for a precise ion beam analysis of elemental depth distributions in near surface layers, the stopping power of the respective ion–target combination must be known sufficiently well. Concerning random stopping, this is true for almost any H or He–target combination [1]. In particular, precise stopping of H, He and B in amorphous Si have been recently published [2–4]. On the other hand, there is a general lack of information concerning the stopping of medium-heavy ions into amorphous Si. These data are badly needed for two main reasons. From the fundamental

point of view, in order to test current theoretical calculation for the electronic energy loss. From the practical one, stopping power data of medium-heavy ions are needed in analytic techniques like elastic recoil detection analysis (ERDA) or heavy ion Rutherford backscattering (HIRBS) in order to perform precise energy to depth conversion.

In the present work, we have measured the Li random stopping power and range straggling into a Si target. With this aim we have used the Rutherford backscattering technique (RBS) together with a multilayer marker system. The advantage of the present experimental arrangement is that it does not make use of thin self-supported films as the ones used in transmission measurements. Then, the present technique allows for stopping power and range straggling measurements at quite low energies. Consequently, we were able to measure the stopping power in a wide energy range interval, between 280 keV and 8.5 MeV, and the range straggling in the 380–2500 keV interval.

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The present results were compared to the previous ones performed in a different and complementary energy interval [5,6] as well as with the predictions of the TRIM program (version 1991) [7] and a semi-empirical universal formula recently proposed by the Kalbitzer group [3].

## 2. Experimental procedure

### 2.1. Li stopping power

For this experiment we have used a Si/Sb multilayer system composed by 8 Sb layers deposited alternately on amorphous Si ones by using the molecular beam epitaxy (MBE) technique. The whole system was grown on top of an SiO<sub>2</sub> film built on an Si(100) substrate. The thickness of the Sb markers was determined by transmission electron microscopy (TEM) to be 2 nm. The average surface roughness of 1 nm as determined with an atomic force microscope is negligible for the present purposes.

The characterization of the samples, that is, the determination of the position of the markers in the (Si/Sb)<sub>8</sub> multilayer was done using a 1–3 MeV He beam provided by the 3 MV Tandatron of the Instituto de Física of Porto Alegre. A solid state detector situated at 170° with respect to the beam normal detected the backscattered He particles. The overall resolution of the electronic system was better than 12 keV. The RBS measurements were done with two geometries, one with the beam normal to the sample (normal geometry) and the second with the sample at four different angles between 20° and 60° with respect to the beam (tilted geometry).

The depth to energy conversion was done using the He stopping data as reported by Niemann et al. [2]. The obtained results are displayed in Table 1. It should be stressed that the quoted values were obtained as an average of eight different measurements at normal and tilted geometries. The errors were calculated taking into account (a) the statistical dispersion of the data, and (b) the reported uncertainties in the He stopping power [2] (around 1%). Other sources of errors, such as geometry, instability of the electronic system are

Table 1

Position of the Sb  $\delta$ -layers from the Si surface.

Marker (layer number)	Depth <sup>a</sup> (nm)
1	53.5
2	144.5
3	233.0
4	375.0
5	546.0
6	861.0
7	1267
8	1690

<sup>a</sup>Typical errors are of the order of 5%.

considered to be much less important. In a second step, we have determined the energy position of the (Sb)<sub>8</sub>Si markers by using the RBS technique with a Li beam, in the same conditions as described above.

In Fig. 1 is shown the RBS spectrum taken with an Li beam corresponding to the multilayer system. As discussed in some detail in [3], for a given beam energy  $E_0$ , at least two independent measurements at different geometries are necessary in order to determine both  $dE/dx$  at  $E_0$  and at  $KE_0$  simultaneously (where  $K$  is the backscattering kinematical factor), in the framework of the mean energy approximation. Then, for each energy we have performed typically five different measurements, and following the procedure described in [4], we have determined for each energy two mean values: one corresponding to  $(dE/dx)_{E_0}$  and the other corresponding to  $(dE/dx)_{KE_0}$ .

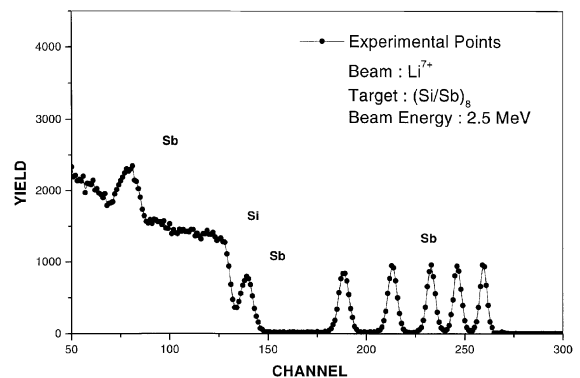


Fig. 1. RBS spectrum of the multilayer system taken with a 2.5 MeV <sup>7</sup>Li beam.

## 2.2. Range straggling

The Li in Si range straggling  $\Omega_S$  was determined from the evaluation of the width of the Sb markers of the  $(\text{Sb})_8\text{Si}$  multilayer system. In order to do that, we have de-convoluted from the total width  $\Omega_T$  of the markers, the contribution of the resolution of the electronic plus detector system and the spread in energy of the accelerator ( $\Omega_E$ ). This last contribution was obtained determining the front edge profile of a 200 nm thick Au film deposited on a Si substrate. Then

$$\Omega_S^2 = \Omega_T^2 - \Omega_E^2.$$

## 3. Results and discussion

In Fig. 2, the Li random stopping powers obtained in the present experiment in the 250 keV–8.5 MeV energy range are shown as full circles. In addition and for comparison, we show the previous published data by Santry and Werner [5] with full line and Jiang et al. [6] with dashed line. At variance with our results, each one of the previously published data cover a different and complementary energy range interval. Inspection of Fig. 2 shows that the Santry et al. data [4] are in quite good agreement with the present one. At the maximum of the curve, there is a small and sys-

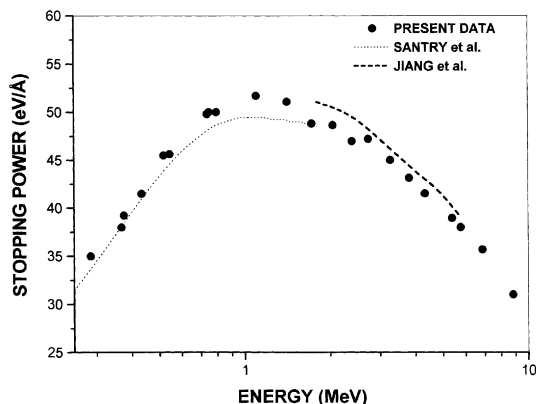


Fig. 2. Present stopping power results as a function of the energy (full circles). For comparison are presented the data of Santry et al. [5] (dotted line) and Jiang et al. [6] (dashed line).

tematic discrepancy which reaches an 8% level. On the other hand, the data of Jiang et al. [6] are systematically higher than ours but the difference is still within the experimental errors.

In Fig. 3 we compare the present experimental results with two semi-empirical calculations. The first corresponds to Ziegler, Biersack and Littmark predictions [1] taken from the program TRIM '95 [7] and the second to the universal algorithm proposed by the Kalbitzer group [3]. It can be observed that for low energies ( $250 < E < 800$  keV), the TRIM predictions agree quite well with our data; however for higher energies they overestimate the experimental results by typically 9%. This is exactly the contrary of what happens with the algorithm proposed by Konac et al. [3]. For high energies there is a quite good experimental-predicted behavior; however for  $E < 1$  MeV, the calculated values are higher than the theoretical ones by typically 10%.

The Li in Si range straggling results normalized to the Bohr straggling are presented in Fig. 4. The error bars are basically due to: (a) data statistical fluctuation in the determination of  $\Omega_T$  and (b) the uncertainty in the  $\Omega_E$  determination. As can be observed for low energies ( $E \leq 1$  MeV), the experimental data are considerably smaller than the Bohr predictions. Then there is a slight overshoot and the data trend approaches the Bohr predictions for energies higher than 2.5 MeV. The theoretical-experimental disagreement observed at

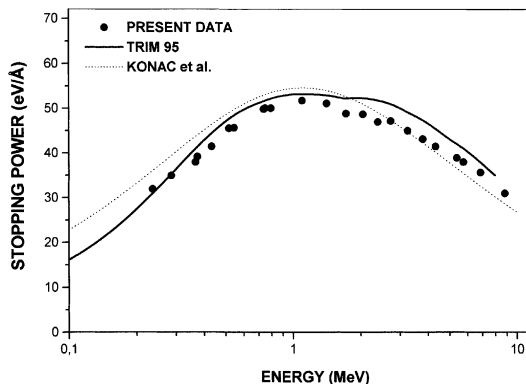


Fig. 3. Present stopping power (full circles) as compared with the semi-empirical calculations done by TRIM '95 [7] (full line), and the “universal formula” by Konac et al. [3] (dotted line).

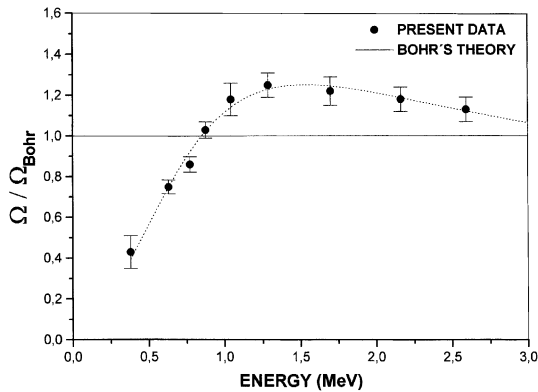


Fig. 4. Present range straggling data normalized to the Bohr straggling. The dashed line is a guide for the eye.

low energies is basically due to the fact that in the Bohr theory all the electrons are considered active. This in fact does not occur, because in the low energy regime only the valence electrons are the active ones.

It is interesting to note that this kind of behavior has been observed for other ion–target combinations, in particular for He and C in Si [3], where the experimental data only reaches the Bohr value for energies of the order of 500 keV/amu, a value which is out of the present experimental regime.

#### 4. Conclusions

In the present work we have studied the Li in Si stopping power in a wide energy interval range ( $280 \geq E \geq 8500$  keV) and the range straggling in a more reduced one ( $380 \geq E \geq 2500$  keV).

Previous published stopping power results determined in smaller and complementary energy ranges have shown an overall good agreement with the present published data. The results of Santry et al. [5] obtained in the low energy range are in good agreement with our results. Only a small and systematic difference has been observed near the maximum of the stopping power curve. On the other hand, the data of Jiang et al. [6] are always

larger than the present one. However, the differences are within the experimental errors.

A comparison with the semi-empirical predictions of the TRIM program and the “universal formula” proposed by the group of Kalbitzer also show an overall good agreement with the present data. However, while the TRIM calculations reproduce quite well the experimental values for low energies, the universal formula shows the same behavior for high energies ( $E > 1.5$  MeV).

Concerning the range straggling data, it should be stressed out that the present are the first experimental results for Li in Si. A comparison with the Bohr straggling indicates a behavior already observed for other ions, that is, for low energy an over-estimation of the experimental results followed by an under-estimation for intermediate energies and a clear tendency for a good experimental–theoretical agreement for  $E \geq 2.5$  MeV.

#### Acknowledgements

This work was partially supported by the International Atomic Energy Agency (IAEA), Contract no. BR-11313/RO.

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