Stopping powers of ^{7}Li, ^{11}B, ^{12}C, ^{14}N, and ^{16}O ions in $C_{16}H_{14}O_3$ polycarbonate

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The stopping powers of bisphenol *A*-polycarbonate $C_{16}H_{14}O_3$ for ^{7}Li, ^{11}B, ^{12}C, ^{14}N, and ^{16}O ions in the 0.5–2.1-MeV/amu energy region have been determined. To avoid direct beam exposure on the film, a modified transmission geometry was used. The areal density of the foil, at exactly the position where the stopping power data were measured, was obtained by combining weighing and proton energy-loss measurements. The experimental stopping powers are compared with predictions of three semiempirical models, which are based on the heavy-ion scaling rule, and with our previous data for the same ions in Mylar. The systematics and deviations of the data from the predicted stopping powers, and the validity of Bragg's additivity rule, are discussed.

I. INTRODUCTION

The uses of the organic material of bisphenol *A* polycarbonate $C_{16}H_{14}O_3$ are many and varied. It is commonly used as a track etch material (*Lexan*, *Macrofol*) for charged-particle detection.[1] Thin porous membranes (*Nuclepore*)[2] are frequently used in environmental air monitoring processes. In the subsequent elemental analysis of the air particulate matter, ion-beam-based techniques are widely employed. In ion-beam analysis methods, in general, polycarbonate is a common target material and thin polycarbonate foils are used for absorbing and stopping radiation. For these purposes the ion stopping powers are needed to calculate the ion energy loss in the material. No experimental stopping power values, however, could be found in the literature for the polycarbonate $C_{16}H_{14}O_3$ for the ions studied prior to the present work.

This study extends our previous stopping power experiments for various ions in different materials to the bisphenol *A* polycarbonate. The aim of the present study was twofold. Firstly, for practical purposes, we wanted to obtain accurate stopping power data for ^{7}Li, ^{11}B, ^{12}C, ^{14}N, and ^{16}O ions in the energy range 0.5–2.1 MeV/amu. Secondly, the present case has a special theoretical interest since bisphenol *A* polycarbonate and Mylar contain the same atomic elements with an almost similar atomic composition (42 at. % H, 48 at. % C, 9 at. % O, and 36 at. % H, 45 at. % C, 18 at. % O, respectively). The stopping powers for Mylar have been determined in our previous studies[3–6] under exactly the same experimental conditions. A comparison of the stopping powers provides a good test of the validity of Bragg's additivity rule.[7]

The experimental stopping powers of this study are compared with the scaled proton stopping powers calculated by two semiempirical models and the TRIM-89 computer code. The first model by Ziegler[8] (abbreviated as *Z*-80) is based on the Z_1-dependent parametrization of the heavy-ion effective charge. It should be noted that in *Z*-80 a separate parametrization for the effective charge of ^{7}Li ions is given. This leads to scaling different from that for all ions heavier than ^{7}Li. The second model by Ziegler, Biersack, and Littmark[9,10] (ZBL-85, ZBL-89) is based on the Brandt-Kitagawa theory.[11] It includes a refined treatment of effective charges and considerations of relative velocities between the ion and the Fermi velocity of electrons in a solid, as well as nuclear shielding in close collisions. The two versions give slightly different stopping powers, we adopted the latter (ZBL-89) for comparisons with our experimental data. The TRIM-89 computer code (version 5.3)[10] uses the theoretical basis of the latter semiempirical model, however, a correction can be made to account for the chemical bonding in compounds such as polycarbonate.[12]

II. EXPERIMENTAL PROCEDURE

The ion beams were supplied by the 5-MV tandem accelerator EGP-10-II of the Accelerator Laboratory of the University of Helsinki. The energy calibration of the beam analyzing magnet was based on the resonances at $E_{lab}(^{15}N) = 6393.6 \pm 1.3$, $13\,356 \pm 4$, $18\,009 \pm 45$, and $24\,409 \pm 45$ keV in the reaction $^{1}H(^{15}N,\alpha\gamma)^{12}C$ and the very thin hydrogen contamination on the surface of a gold target.[13] A standard silicon surface-barrier detector (100 μm, 50 mm^2) was used.

The experimental system used in the transmission experiments is described in detail in Ref. 6. In brief, the sample foil was interposed into the scattered ion beam from a gold target in front of the detector. The most probable energy loss of the ions transmitted through the foil was obtained by subtracting the energy of the gold scattering signal from that measured without the foil. The characteristics of the ion beams are also given in Ref. 6.

In order to extract the stopping powers from the energy-loss data, the areal density of the foil was determined by weighing. The homogeneity of the foil was checked by 2.0–4.0-MeV proton energy-loss measurements from several different spots on the foil. The aver-

age energy-loss value thus obtained was then compared with the proton energy-loss measurement in the same geometry and at exactly the same spot on the foil as the actual heavy-ion energy loss. Within experimental accuracy (±2%) no differences were observed. In this way we could confirm that the weighed areal density obtained corresponds to the effective local areal density used in the actual heavy-ion energy-loss measurements. A thickness value of 9.88 μm was obtained for the foil with a nominal thickness of 10 μm and a specific gravity of 1.20 g/cm^3 as given by the manufacturer (Nuclepore Corporation).

III. RESULTS

The stopping power at the mean ion energy E_{av} in the foil was calculated by dividing the energy loss δE by the foil areal density $N\delta x$ (N atomic density, δx foil thickness).

To account for the nonlinear dependence of the stopping powers on ion energy, a small correction[14,4] to the mean energy E_{av} was applied. As a result, the stopping power $S = dE/dx$ (differential energy loss per unit path length) is taken as $\delta E/\delta x$ at an effective ion energy E_{eff}. The correction procedure for E_{eff} is valid only when $\delta E < E_{av}$. In the case of large energy-loss values the stopping powers based on only experimental data can not be extracted without any assumption about the stopping power curve.

The stopping powers of bisphenol A polycarbonate for ^{7}Li, ^{11}B, ^{12}C, ^{14}N, and ^{16}O ions as a function of effective ion energy $E = E_{eff}$ are presented in Table I. To illustrate the overall behavior of the stopping powers, and to present the predictions of the semiempirical models, the stopping powers are plotted in Fig. 1.

The data are assigned an absolute uncertainty of ±3%.

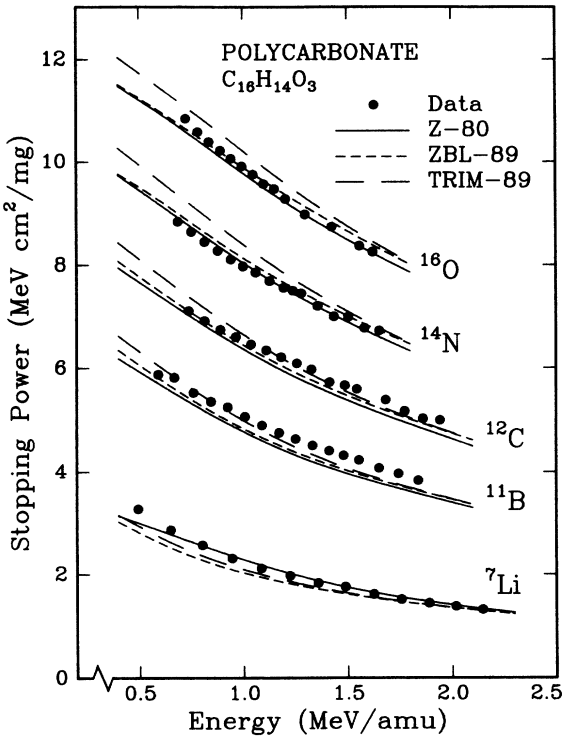

FIG. 1. Stopping powers of ^{7}Li, ^{11}B, ^{12}C, ^{14}N, and ^{16}O ions in $C_{16}H_{14}O_3$ polycarbonate in the ion energy range 0.5–2.1 MeV/amu. The curves represent the stopping powers as predicted by the various semiempirical scaling models.

This includes the possible 2% error arising from the determination of the foil thickness by weighing and uncertainties in the measurement of δE. Excluding the possible error in the foil thickness, the relative uncertainty between measurements for the different ions is less than 1%.

TABLE I. Stopping powers of ^{7}Li, ^{11}B, ^{12}C, ^{14}N, and ^{16}O ions in $C_{16}H_{14}O_3$ polycarbonate in the ion energy range E = 0.5–2.1 MeV/amu.

				Stopping Power (MeV cm^2/mg)					
E (MeV/amu)	^{7}Li	E (MeV/amu)	^{11}B	E (MeV/amu)	^{12}C	E (MeV/amu)	^{14}N	E (MeV/amu)	^{16}O
0.495	3.21	0.592	5.77	0.739	6.98	0.688	8.67	0.726	10.65
0.651	2.81	0.670	5.71	0.816	6.79	0.753	8.48	0.784	10.39
0.803	2.52	0.761	5.42	0.891	6.62	0.816	8.29	0.838	10.20
0.946	2.27	0.845	5.25	0.965	6.48	0.879	8.12	0.892	10.03
1.086	2.08	0.925	5.15	1.038	6.34	0.942	7.96	0.944	9.88
1.223	1.94	1.008	4.97	1.111	6.23	1.001	7.83	0.996	9.73
1.358	1.80	1.090	4.81	1.183	6.10	1.062	7.71	1.049	9.57
1.489	1.73	1.172	4.67	1.257	5.98	1.128	7.55	1.101	9.39
1.625	1.59	1.251	4.55	1.328	5.86	1.196	7.42	1.152	9.29
1.757	1.49	1.332	4.43	1.415	5.62	1.241	7.36	1.205	9.10
1.889	1.42	1.411	4.33	1.487	5.56	1.281	7.31	1.299	8.80
2.018	1.36	1.482	4.24	1.545	5.49	1.359	7.07	1.427	8.57
2.147	1.30	1.555	4.15	1.683	5.28	1.436	6.87	1.559	8.21
		1.649	4.00	1.773	5.07	1.505	6.86	1.623	8.10
		1.743	3.89	1.861	4.93	1.582	6.65		
		1.838	3.76	1.943	4.90	1.653	6.60		

IV. DISCUSSION

The heavy-ion stopping powers based on the Ziegler parameters for scaling proton stopping powers (Z-80), those based on the Brandt-Kitagawa theory (ZBL-89), and stopping powers calculated by the TRIM-89 computer code, are presented together with our experimental data in Fig. 1. Bragg's additivity rule has been used in conjunction with the Z-80 and ZBL-89 models. In the curves referred to as TRIM-89, a correction to account for the chemical bonding of the bisphenol A polycarbonate has been added.

No experimental comparisons are possible due to the lack of previous data. In general, when comparing the experimental stopping powers with the semiempirical predictions, only a fair agreement is observed in the best cases. The Z-80 or ZBL-89 models appear to be most appropriate for calculating ^{14}N and ^{16}O stopping powers in the present energy range. However, the TRIM-89 model including the bonding corrections, provided the most successful fits for ^{11}B and ^{12}C ions. The ^{7}Li data seem to be best fitted by the Z-80 curves. No single model thus reproduces all the data accurately and none of them predicts the stopping power values significantly better than the others for every case.

The stopping power dependence on the projectile charge, the Z_1 oscillation, is matched only reasonably by the models. The ZBL-89 curves, for example, fall 3–5% below the ^{11}B and ^{12}C data but exceed the ^{14}N and ^{16}O data by 2–3% in the energy interval 1–2 MeV/amu. The same trend is evident for the TRIM-89 calculations.

The comparison of the stopping powers between compound materials of similar atomic composition provides information of the stopping power dependence on the target chemical structure. The stopping powers of ^{7}Li, ^{11}B, ^{12}C, ^{14}N, and ^{16}O ions in Mylar ($C_{10}H_8O_4$) have been measured previously by us using the same experimental setup.[5,6] The atomic contents in Mylar and bisphenol A polycarbonate —45% and 48% of carbon, 36% and 42% of hydrogen, and 18% and 9% of oxygen, respectively—are very similar for the three elements. The possible difference observed in the stopping power behavior between polycarbonate and Mylar in comparison with the semiempirical predictions calculated using Bragg's additivity rule is due to chemical effects. In this case, the uncertainties in the stopping powers of the elements may produce only an insignificant effect in the relative stopping powers of the two materials. The comparison of the stopping powers in these compounds thus constitutes a good test for the validity of Bragg's additivity rule.

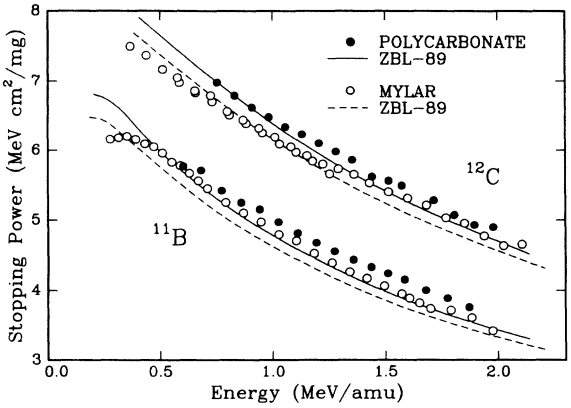

FIG. 3. Comparison of stopping powers as in Fig. 2 but for ^{11}B and ^{12}C ions.

Figures 2–4 illustrate the comparison of the experimental stopping power values for bisphenol A polycarbonate and Mylar. The Z-80 curves for ^{7}Li and the ZBL-89 predictions for the heavier ions are also plotted. A strikingly similar stopping power behavior for each of the ions ^{11}B, ^{12}C, ^{14}N, and ^{16}O (Figs. 3 and 4) in polycarbonate and Mylar may be observed in comparison to the semiempirical curves. We find exactly the same deviations and Z_1 oscillations for both of the materials. The similarity in the case of ^{7}Li stopping powers is not so evident, possibly because of an insufficient experimental accuracy to adequately resolve the slight predicted difference in the stopping powers of the two compounds. The situation for ^{7}Li is not affected by the choice of the semiempirical model.

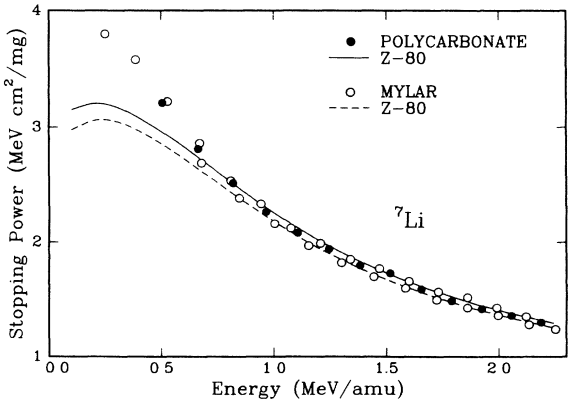

FIG. 2. Comparison of the stopping powers of ^{7}Li ions in $C_{16}H_{14}O_3$ polycarbonate and Mylar.

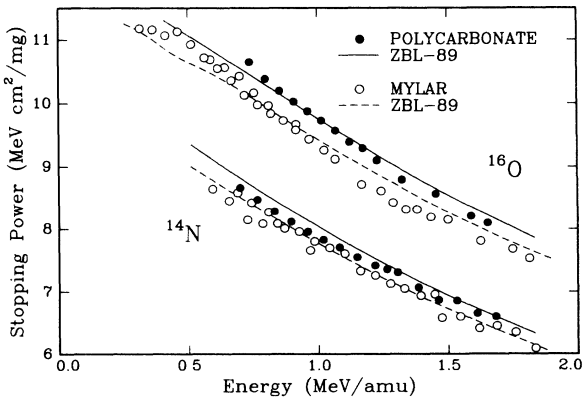

FIG. 4. Comparison of stopping powers as in Fig. 2 but for ^{14}N and ^{16}O ions.

The similarity evident in the ion stopping power behavior in polycarbonate and Mylar when compared to semiempirical predictions obtained using Bragg's rule is a clear indication of the validity of Bragg's rule in these compound materials.

The theoretical corrections[10,12] to Bragg's rule, arising from the chemical bonding effects, amount to 2.0% for Mylar and 4.4% for bisphenol *A* polycarbonate at the stopping power maxima. These corrections are independent of the projectile and gradually decrease towards higher energies, falling to 1.5% and 3.3% at 1.0 MeV/amu, respectively. These small corrections are, however, observed to be overrun by the pronounced Z_1 oscillations as seen in Fig. 1.

ACKNOWLEDGMENTS

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