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Polycarbonate, Mylar and Havar stopping powers for 1.0–3.25 MeV/nucleon ^{40}Ar-ions

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Abstract

Stopping powers of polycarbonate, Mylar and Havar for 1.0–3.25 MeV/nucleon ^{40}Ar-ions have been determined by the transmission method in two geometries. The stopping power values were obtained within uncertainty of 2.1–4.5% for the various materials. The present results are compared with the predictions obtained by the most commonly used procedures employed in obtaining stopping powers. These include the Northcliffe and Schilling model, semi-empirical parametrization of Ziegler *et al* (SRIM2000) with and without the cores and bonds model and the Hubert *et al* formulation. SRIM2000 values were in good agreement in case of Mylar and Havar, on average within 3% of present results. For polycarbonate the differences were less than 6% on average. The cores and bonds (CAB) model improved the parametrization values slightly. The Northcliffe and Schilling model and the Hubert *et al* formulation both yielded values within 5% or less for Mylar and polycarbonate. For the Havar the Hubert *et al* formulation and the present results disagreed by 10% on average.

1. Introduction

Knowledge of the stopping powers of energetic ions in different kinds of materials is of importance for understanding fundamental atomic processes and in applied physics. Due to a limited number of experimental data available for heavy ions their stopping power values are mainly based on various theoretical predictions. Therefore stopping powers of elemental materials and especially compound materials need to be further investigated. Also, this new experimental data can be used for the development and checking of semi-empirical parametrizations and to improve theoretical predictions. The purpose of this work is to obtain new accurate experimental data for technologically important ion–material combinations. No previous stopping power data for the presently studied ion–material combinations were found

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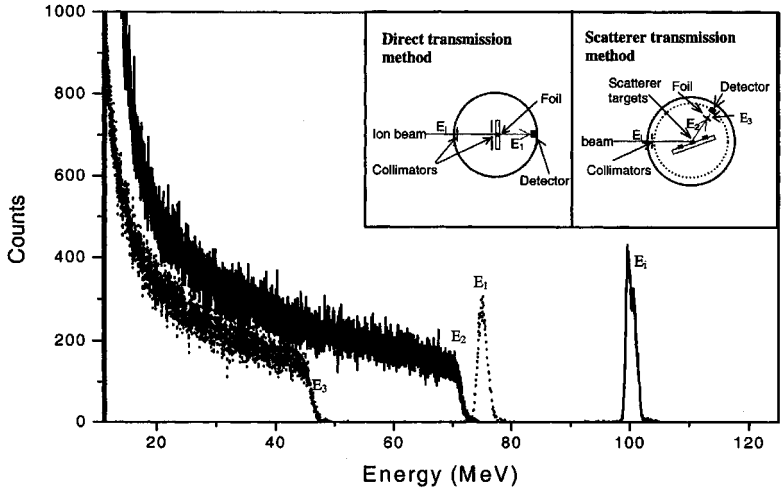

Figure 1. Typical direct and scatterer transmission method spectra obtained with 100 MeV ^{40}Ar ions for Havar. In the direct transmission method E_i corresponds to the initial ion energy and E_1 to the energy after the foil ($\Delta E = E_i - E_1$). In the transmission method employing a scattering target E_2 is the ion energy after scattering to an angle of 75° and E_3 the corresponding energy after the foil ($\Delta E = E_2 - E_3$). The insets show the experimental arrangements together with the appropriate energy labels.

in a data bank based literature search. Materials of interest have been selected because of their wide use in various applications, such as absorbers, windows, particle identification and radiation detection. Ar ions were selected for their wide use in different areas of ion beam physics, for example in elastic recoil detection (ERD) studies.

2. Experimental methods

The K130 cyclotron at the Accelerator Laboratory of the University of Jyväskylä supplied the ^{40}Ar-ion beams. The energies of the ^{40}Ar-ions were 80, 100 and 150 MeV. The scattering chamber used for radiation electron tests [1] was employed in the measurements and a pin diode (area 100 mm^2, thickness 300 μm) was used for particle detection. The beam spot sizes on the studied foils in the direct beam measurements and on the targets in the scattering experiments were limited to 5 mm in diameter by using slits and apertures.

Two different experimental transmission arrangements were employed (see the insets in figure 1). The direct exposure of the Mylar and Havar foils to the ion beam was used with the energies of 80 and 100 MeV (detector placed at 0°). The amount of particles per second on the studied foil was about 500. All foils were attached to a linear movement assembly, which made it possible to do all the measurements without breaking the vacuum of the chamber.

In the other arrangement thick targets of elements Nb, In, Ta and Bi were used first to scatter the particle beam. These targets were attached to the linear movement assembly and the detector was attached to the chamber floor, which allowed it to rotate 180°. Several different scattering angles were used varying from 25° up to 120°. The rotation of the detector combined with different scatterer targets enables measurements with several ion energies without tuning the accelerator.

In the transmission method the energy loss of the particles is determined by observing the decrease of ion energy in the studied foil. In figure 1 typical spectra obtained by using both

Table 1. Nominal compositions, average atomic weights, specific gravities and areal densities for the studied polycarbonate, Mylar and Havar materials.

Material	Element	Concentration (at. %)
Polycarbonate $(C_{16}H_{14}O_3)_x$		
$M = 7.70$ amu	H	42.4
$\rho = 1.22$ g cm^{-3}	C	48.5
$\rho_{\text{areal}} = (224 \pm 5)$ μg cm^{-2}	O	9.1
Mylar $(C_{10}H_8O_4)_x$		
(polyethylene terephthalate)	H	36.4
$M = 8.73$ amu	C	45.4
$\rho = 1.39$ g cm^{-3}	O	12.8
$\rho_{\text{areal}} = (824 \pm 17)$ μg cm^{-2}		
Havar		
$M = 57.6$ amu	Be	0.3
$\rho = 8.30$ g cm^{-3}	C	1.0
$\rho_{\text{areal}} = (1.845 \pm 0.010)$ mg cm^{-2}	Cr	22.2
	Mn	1.7
	Fe	18.1
	Co	41.6
	Ni	12.8
	Mo	1.4
	W	0.9

the transmission technique variations are shown for 100 MeV ^{40}Ar ions in Havar. If the areal density of the foil is known, the transmission method enables the stopping power determination by simply dividing the energy loss by the areal density.

2.1. Foil thickness determination

The areal densities of the foils were determined by two procedures. The actual areal densities of the foils were determined by weighing circular (ϕ20 mm) pieces of the foils. These weighed pieces of the foils were used in the measurements. The areal densities were also checked by measuring the energy loss of alpha particles from a ^{226}Ra radioactive source and using reference stopping powers [2]. The areal densities obtained by alpha particle energy loss were within 2% of the weighed values. The weighed values were adopted as actual foil thicknesses. The obtained average areal densities were (224 ± 5) μg cm^{-2} for polycarbonate, (824 ± 17) μg cm^{-2} for Mylar, and (1.845 ± 0.010) mg cm^{-2} for Havar. The foil homogeneity was checked by alpha particle energy loss measurements from several points of the foil. The inhomogeneities were less than 1% in all cases and they have been taken into account in the foil thickness uncertainties. The studied materials and foil properties are presented in table 1.

Charged particle bombardment can break the electronic bonds of the molecular compound. It may also result in molecular fragment recombination to form new molecular bonds. These effects can affect the organic foils and change their properties, i.e. the stopping power values. In the present experiments the fluences the materials are exposed to can be estimated from the measured energy spectra. The total fluence for the foils is clearly less than 10^8 particles per cm^2. The needed fluence to produce appreciable deterioration of polycarbonate according to the findings of [3] is about 10^{12} particles per cm^2 for 1.0 MeV He ions. When the Ar ion energy loss is calculated for a polycarbonate foil having the same thickness as in the present experiment and using the maximum stopping power value, it can be noted that the energy

deposited by the Ar ions is less than ten times more than that of the 1 MeV He ions. The total energy deposited by the Ar ions in the present experiments is thus clearly below the deterioration limit and need not be taken into account.

2.2. Data analysis

As a first step in the analysis, the spectra have to be fitted to obtain the peak (direct exposure) or backscattering edge (with scatterers) positions. A Gaussian curve was fitted to the peaks and the procedure described in detail in [4] was used for fitting the backscattering edges. The uncertainties in the peak and edge positions were 0.1–0.3 and 1 channel, respectively. For the detector energy calibration the measurements without the foil were used and the detection system featured linear energy dependence. The initial ion energies were calculated from the accelerator parameters providing values with an uncertainty of less than 1%.

The most probable energy loss of the ions transmitted through the foil was obtained from the reduction of the ion energy by observing the shift of the peak or edge position. According to the obtained spectra, the displacement between the average energy loss and the most probable energy loss was negligible.

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 ($\rho\Delta x$) (ρ represents mass density, Δx is the foil thickness, and $E_{av} = E_i - \Delta E/2$, where E_i is the incident ion energy). To account for the nonlinear ion energy dependence of stopping powers, a small correction to the mean energy (E_{av}) was applied [5]. As a result, the stopping power, $S = -(1/\rho)(\mathrm{d}E/\mathrm{d}x)$ (differential energy loss per unit path length), is taken as $\Delta E/\rho\Delta x$ 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, stopping powers based only on experimental data cannot be extracted without any assumption of the stopping power curve shape.

The estimated errors in the energy loss values are 2% for the direct beam experiments and 3.5–4% for the scatterer experiments, including the uncertainty due to the energy calibration procedure. The uncertainty in the adopted areal density value for Havar is 0.5 and 2.2% for polycarbonate and 2.1% for Mylar. These arise from the possible uncertainties in the weighing procedure and the non-uniformity of the foils. The uncertainties in the stopping power values are thus estimated to be 2.1% for Havar and 2.8% for Mylar and polycarbonate in the values obtained by the direct beam measurements and 3.5–4.5% for the values obtained by the scatterers, respectively.

3. Results and discussion

The experimental results are summarized in table 2 where the stopping power values are presented as a function of the effective ion energy together with the predictions of the most frequently used stopping power parametrizations. In the following the present experimental results are compared in more detail with these predictions.

3.1. Comparison with the SRIM2000 parametrizations and the Northcliffe and Schilling semiempirical tabulations

The experimental results are presented in figure 2 together with the predictions of the commonly, especially in ion beam based materials research, employed SRIM2000 (version 2000.09) parametrization [2].

The SRIM2000 parametrization values agree rather well with the present experimental values, even though clear systematic differences can be seen. The parametrization slightly

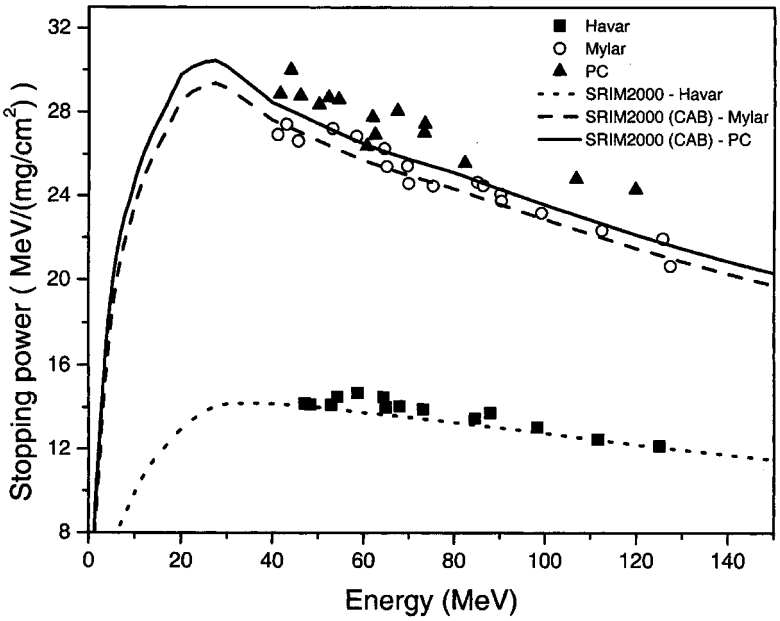

Figure 2. The experimental stopping power values of polycarbonate, Mylar and Havar for ^{40}Ar ions. The values obtained by the SRIM2000 parametrization are shown by the solid and dashed lines. In case of polycarbonate and Mylar the SRIM2000 values include the CAB corrections.

underestimates the experimental values in the whole energy interval. The observed maximum differences in the experimental and SRIM2000 values are 9.2% for polycarbonate, 4.9% for Mylar and 7.5% for Havar. The average differences are 6.0, 2.3 and 2.6%, respectively. The cores and bonds (CAB) correction [6] for polycarbonate and Mylar improves slightly the situation. The average differences are 2.0% for Mylar and 4.8% for polycarbonate. For Havar there is naturally no CAB correction available.

The tabulated stopping power values of Northcliffe and Schilling [7] are based on a scaling law. The basic assumption of the scaling law is, that the stopping power ratio of two different materials is independent of the ion at a specific ion velocity. It is also assumed that the relative stopping power based on the scaling law varies smoothly as a function of the atomic number (Z_2) of the stopping media and the ion energy (E/m_2). Furthermore, it is assumed that the stopping powers of all materials change smoothly as a function of the ion atomic number (Z_1) and energy (E/m_1).

At energies above 50 MeV the Northcliffe and Schilling predictions seem to underestimate the present results. The differences between experimental and predicted values increase with the ion energy up to 10% at 120 MeV. At ion energies of 50 MeV and below the polycarbonate values are in good agreement while the Mylar experimental values are overestimated by the Northcliffe and Schilling values.

3.2. Comparison to the Hubert et al semiempirical formulation

The Hubert *et al* parametrization [8] is based on the scaling of fully stripped He ion stopping powers. Heavy ion stopping power S_{HI} for a fixed medium and ion velocity combination is calculated by means of the well known scaling law

$$S_{\mathrm{HI}} = \frac{S_{\mathrm{He}}}{\gamma_{\mathrm{He}}^2 Z_{\mathrm{He}}^2}(\gamma_{\mathrm{HI}} Z_{\mathrm{HI}})^2 \tag{1}$$

Table 2. Stopping powers of Mylar, polycarbonate and Havar in units of MeV/(mg cm^{-2}) as a function of ion effective energy. The differences between the present values and the predictions of the various parametrizations are given in units of per cent in the parenthesis.

	Energy (MeV)	Present	SRIM2000	SRIM2000(CAB)	Northcliffe and Schilling	Hubert *et al*
Mylar	41.2	26.9	26.6(−1.1)	27.5(+2.1)	28.3(+5.3)	27.7(+3.1)
	43.1	27.4	26.5(−3.3)	27.3(−0.4)	28.1(+2.5)	27.9(+1.7)
	45.6	26.6	26.3(−1.0)	27.1(+1.8)	27.8(+4.4)	28.0(+5.2)
	53.2	27.2	25.9(−4.8)	26.4(−2.9)	26.8(−1.4)	27.9(+2.7)
	58.4	26.9	25.6(−4.9)	26.0(−3.4)	26.2(−2.8)	27.7(+2.8)
	64.5	26.3	25.2(−4.2)	25.5(−3.1)	25.4(−3.4)	27.2(+3.5)
	65.1	25.4	25.2(−1.0)	25.4(+0.2)	25.3(−0.2)	27.2(+7.0)
	69.6	25.5	24.9(−2.4)	25.1(−1.6)	24.8(−2.6)	26.8(+5.1)
	69.9	24.6[a]	24.9(+1.0)	25.1(+1.9)	24.8(+0.8)	26.8(+8.8)
	75.3	24.5	24.5(+0.1)	24.6(+0.6)	24.2(−1.1)	26.3(+7.3)
	85.0	24.7	23.9(−3.3)	23.9(−3.2)	23.3(−5.7)	25.4(+2.9)
	86.3	24.5	23.8(−2.8)	23.8(−2.8)	23.2(−5.5)	25.3(+3.2)
	90.2	24.1[a]	23.6(−2.3)	23.5(−2.4)	22.8(−5.4)	25.0(+3.6)
	90.3	23.8	23.6(−1.0)	23.5(−1.2)	22.8(−4.3)	25.0(+4.8)
	99.2	23.2	23.0(−1.0)	22.9(−1.3)	22.0(−5.2)	24.2(+4.5)
	112.5	22.4	22.1(−1.5)	22.0 (−1.7)	20.9(−6.5)	23.3(+4.2)
	125.8	22.0	21.1(−3.9)	21.2 (−3.7)	20.0(−9.1)	22.6(+2.9)
	127.4	20.7	21.0(+1.6)	21.1 (+1.9)	19.9(−3.9)	22.6(+9.1)
Polycarbonate	41.7	28.9	27.4(−5.3)	28.2(−2.3)	29.7(+2.7)	27.9(−3.5)
	44.1	30.0	27.2(−9.2)	28.0(−6.6)	29.4(−2.1)	28.1(−6.4)
	46.1	28.8	27.1(−5.9)	27.8(−3.3)	29.1(+1.0)	28.2(−2.2)
	50.2	28.4	26.9(−5.4)	27.5(−3.2)	28.5(+0.4)	28.2(−0.7)
	52.3	28.7	26.7(−6.9)	27.3(−4.9)	28.2(−1.7)	28.2(−1.8)
	54.5	28.6	26.6(−7.0)	27.1(−5.2)	27.9(−2.4)	28.1(−1.7)
	60.7	26.4	26.2(−0.8)	26.6(+0.7)	27.1(+2.5)	27.8(+5.2)
	61.9	27.8	26.1(−6.0)	26.5(−4.7)	26.9(−3.3)	27.7(−0.4)
	62.5	26.9	26.1(−3.0)	26.4(−1.7)	26.8(−0.3)	27.6(+2.8)
	67.5	28.1	25.8(−8.3)	26.0(−7.4)	26.2(−6.8)	27.2(−3.1)
	73.4	27.0	25.4(−6.0)	25.6(−5.3)	25.5(−5.6)	26.7(−1.1)
	73.5	27.5	25.4(−7.7)	25.6(−7.1)	25.5(−7.4)	26.7(−2.9)
	82.2	25.6	24.8(−3.1)	24.9(−2.8)	24.5(−4.2)	25.9(+1.1)
	106.8	24.9	23.2(−7.0)	23.1(−7.4)	22.2(−11)	23.8(−4.5)
	119.8	24.3	22.3(−8.4)	22.2(−8.7)	21.1(−13)	22.9(−5.7)
Havar	47.1	14.2	14.1(−0.8)			12.7 (−10.5)
	48.4	14.2	14.1(−1.0)			12.8(−9.9)
	52.9	14.1	14.0(−1.0)			13.0(−7.8)
	54.3	14.5	13.9(−4.0)			13.0(−10.1)
	58.8	14.7	13.8 (−6.0)			13.1 (−11.1)
	64.4	14.5	13.7 (−5.6)			13.0 (−10.5)
	64.9	14.0	13.7 (−2.3)			13.0 (−7.4)
	68.0	14.7[a]	13.6 (−7.5)			12.8 (−12.6)
	73.2	13.9	13.5 (−3.1)			12.6 (−9.5)
	84.5	13.5	13.2 (−2.3)			
	88.0	13.7[a]	13.1 (−4.4)			
	98.3	13.1	12.8 (−2.0)			
	111.7	12.5	12.5 (−0.2)			
	125.1	12.2	12.1 (−0.8)			

[a] Values have been obtained by the direct beam exposure geometry.

where γ_{HI} is the heavy ion effective charge and γ_{He} is the helium ion effective charge which for a fully stripped He ion is $\gamma_{\mathrm{He}} = 1$. Z_{HI} and Z_{He} are the atomic numbers of the heavy and helium ions. S_{He} is the stopping power for helium ions in the same medium with the same velocity as for the heavy ions. The effective charge of the heavy ion is obtained by the parametrization

$$\gamma_{\mathrm{HI}} = 1 - X_1 \exp(-X_2(E/A)^{X_3}, Z_{\mathrm{HI}}^{-X_4}) \tag{2}$$

where (E/A) is the energy per nucleon in MeV/u and $X_1, \ldots, X_4$ are the best fit parameters given by Hubert *et al* [8].

The procedure is valid when the He ions are fully stripped, i.e. $E/A \geqslant 2.5$ MeV/u. When the ion energy is less than 2.5 MeV/u, we have to use a parametrization also for the helium effective charge. To realize this the parametrization by Ziegler *et al* has been utilized [9]. The effective charge of helium ions is presented as

$$\gamma_{\mathrm{He}}^2 = 1 - \exp\left(- \sum_0^5 a_i \ln(E/A) \right) \tag{3}$$

where a_i are the fitting parameters given by Ziegler *et al* and (E/A) is the He ion energy per nucleon in keV/u. The major assumption of this helium ion effective charge parametrization is that the effective charge does not depend on the target material. Nevertheless, with the present ion energies (1.0–3.25 MeV/u) the Ziegler *et al* parametrization for the He ion effective charge is always 1, i.e. the basic Hubert *et al* parametrization is valid also at these low ion energies.

To employ the Hubert *et al* formulation experimental He ion stopping power data is needed at the same ion velocity. In our case the corresponding helium ion energies range from 4.1 to 12.7 MeV. Unfortunately, most reliable measurements for the presently interesting materials have been made at He ion energies below 8 MeV. In this paper we have employed the Hubert *et al* formulation only for heavy ion energies having corresponding He data. For Mylar and polycarbonate the used reference stopping power values have been taken from the ICRU report [10] and for Havar from [11].

As can be noted from the values presented in table 2 for Havar the Hubert *et al* values underestimate the experimental values by about 10%. The scaling law also predicts the stopping power maximum at about 55–60 MeV for Ar ions in Havar. The present results do not confirm or over-rule this possibility. For Mylar the predictions overestimate and for polycarbonate underestimate the measured values by 4.6 and 2.9% on average, respectively. For these materials the predicted stopping power curve maximum is between 45 and 50 MeV. The present results suggest that the stopping power maximum for polycarbonate would be at a lower energy than indicated by the Hubert *et al* formulation. In the case of Mylar the present results do not overrule this possibility.

4. Conclusions

We have determined the stopping powers of polycarbonate, Mylar and Havar for ^{40}Ar ions in the energy range of 1.0–3.25 MeV/u. The total uncertainty is less than 2.8% for the values obtained by the direct transmission geometry and less than 4.5% for the values obtained by the scattering transmission geometry. The results obtained with both methods were in good mutual agreement. We have shown that for Mylar and polycarbonate SRIM2000, SRIM2000 with the CAB corrections, Northcliffe and Schilling, and the Hubert *et al* procedures can all be successfully employed within experimental accuracy in the energy region of 1.0–3.25 MeV/u. For Havar SRIM2000 gave good correspondence with present results while the Hubert *et al* method underestimated the present results by 10%.

Acknowledgments

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