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Stopping powers and energy loss of 3–22-MeV ^{12}C ions in Havar, nickel, Kapton, and Mylar

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Stopping-power values and energy losses of 3.4–22.0-MeV $^{12}C^{n+}$ ions were measured in the transmission geometry for 2.0-μm Havar, 2.8-μm nickel, 9.27-μm Kapton, and 3.8-μm and 6.9-μm Mylar foils. The experimental data were compared with calculated predictions obtained by using Bragg's additivity rule and using the Andersen-Ziegler parameters for proton stopping with appropriate scaling for carbon ions. Furthermore, the data were compared with experimental values available in the literature. A distinct disagreement between the present results and calculated predictions was observed in the case of Havar and nickel.

I. INTRODUCTION

The knowledge of stopping powers and energy losses of heavy charged particles in various foil materials is of significant interest in many applications involving heavy ions, and in theoretical considerations. Little experimental work has been carried out with carbon ions used for obtaining stopping values, especially in the composite foils of Havar, Kapton, and Mylar. In the case of Mylar only the energy-loss data given by Schambra *et al.*[1] may be found in the literature. No experiments have been performed for Havar and Kapton. More experimental stopping data exist for elemental materials. Porat and Ramavataram[2] have measured the stopping power in nickel in the energy interval 0.36–3.2 MeV. Ved'manov *et al.*[3] have evaluated the stopping-power curve shape in nickel in the energy interval of 1–8.8 MeV and Roll and Steigert[4] have determined the stopping power for the energies of 12–120 Mev. Iwase *et al.*[5] have also determined stopping-power values in nickel at higher carbon-ion energies of 83–105 MeV.

Using the transmission technique, we have measured the stopping power and energy loss of 3.4–22.0-MeV ^{12}C ions in 2.0-μm Havar, 2.8-μm nickel, 9.27-μm Kapton, and in 3.8-μm and 6.9-μm Mylar foils. The present work is a continuation of our systematic study[6–9] for obtaining accurate stopping-power and energy-loss data for energetic ions in Havar, nickel, Kapton, and Mylar. By performing a series of systematic measurements using the same experimental method and apparatus we hope to reduce the relative uncertainty of the data. Although uncertainties less than 5% are generally quoted for the stopping powers in the literature, the spread between different measurements often exceeds 10%.

II. EXPERIMENTAL METHODS

The carbon-ion beams were obtained from the 5-MV EGP-10-II tandem accelerator. A beam of $^{12}C^{+}$ was used for energies between 2 and 3 MeV, and $^{12}C^{2+}$, $^{12}C^{3+}$, and $^{12}C^{4+}$ beams were chosen for energy ranges 4–9 MeV, 10–15 MeV, and $\gtrsim 16$ MeV, respectively. Proton backscattering was used to determine the foil thickness. The proton beam was generated by the 2.5-MV Van de Graaff accelerator.

The energy-loss measurements were performed in transmission geometry by placing the sample foils into the carbon-ion beam scattered from a thick gold target. More details of the experimental arrangement may be found in Ref. 6. The most probable energy loss of the ions in the foil was determined by observing the shift of the backscattering signal, induced by the foil. The detector (50-mm^2, 100-μm silicon surface barrier) was positioned at a scattering angle of 150° so that the detector solid angle was 4 mSr. Because only the metallic foils of Havar and nickel may be exposed to direct beam,[6,7] the use of a scatterer is necessary to obtain a sufficiently-low-intensity ion flux. Several data points were also measured by placing the metal foils in the direct beam. The energy resolution of the detection system was 105 keV at $E_C = 15.9$ MeV.

III. MEASUREMENTS AND RESULTS

The areal densities of the foils were measured after the carbon-ion experiments by 2.0–2.3-MeV proton backscattering. The stopping powers of Ref. 10 were assumed. In determining the foil thickness the nominal mass densities of 8.30, 8.91, 1.42, and 1.39 g/cm^3 for Havar, nickel, Kapton, and Mylar, respectively, were used (for details see Ref. 9). An accuracy of 2% was estimated for the resulting foil thicknesses given in Table II.

The obtained stopping-power values of the foil materials are summarized in Table I. Mean ion energies in the foils, corrected for the nonlinear dependence of the stopping powers on energy, were adopted. The method of extracting the stopping from the energy-loss data given in Table II and the approximations and their validity are described in detail in Refs. 8 and 9. The uncertainties of the energy-loss data are estimated from the possible ex-

TABLE I. The stopping-power values of ^{12}C ions for Mylar, Havar, nickel, and Kapton.

			Stopping power (MeV cm^2/mg)				
E (MeV)	Mylar	E (MeV)	Havar	E (MeV)	nickel	E (MeV)	Kapton
16.04	5.65[a]	19.32	3.17	18.06	3.13	13.51	5.89
15.22	5.73[a]	18.28	3.21	16.99	3.17	12.60	6.04
14.76	5.66[b]	17.23	3.27	15.92	3.22	11.70	6.17
14.41	5.80[a]	16.21	3.29	14.86	3.27	10.78	6.31
13.87	5.84[b]	15.12	3.38	13.79	3.31	9.86	6.47
13.58	5.92[a]	14.70	3.32	13.22	3.36	8.95	6.61
13.01	5.97[b]	14.11	3.40	12.33	3.42		
12.74	6.05[a]	13.85	3.36	11.48	3.45		
12.14	6.09[b]	13.05	3.45	10.61	3.49		
11.91	6.19[a]	13.00	3.42	9.74	3.52		
11.25	6.25[b]	12.14	3.48	8.90	3.55		
11.07	6.32[a]	11.99	3.51				
10.39	6.39[b]	11.28	3.55				
10.24	6.44[a]	10.94	3.57				
9.52	6.51[b]	10.44	3.60				
9.41	6.56[a]	9.58	3.65				
8.62	6.70[b]	8.74	3.70				
8.54	6.79[a]	7.90	3.71				
7.74	6.83[a]	7.06	3.74				
7.71	6.86[b]	6.29	3.69				
6.89	6.98[a]						
6.79	7.05[b]						
6.03	7.17[a]						
5.17	7.37[a]						
4.32	7.50[a]						

[a] From 3.73-μm foil data.

[b] From 6.86-μm foil data.

perimental errors in determining signal positions in the ^{12}C energy loss and ^{1}H backscattering measurements. Taking into account the possible errors in energy loss and foil thickness, we estimate the uncertainties of the stopping powers to fall below 3%. Figures 1 and 2 show the experimental data, together with calculated semiempirical predictions given by Bragg's rule when used in conjunction with scaled[11] proton stopping parameters by Andersen and Ziegler.[10]

A small correction to a few energy-loss data points at the low-energy end was needed to take into account the effect of nonconstant particle energy per channel due to

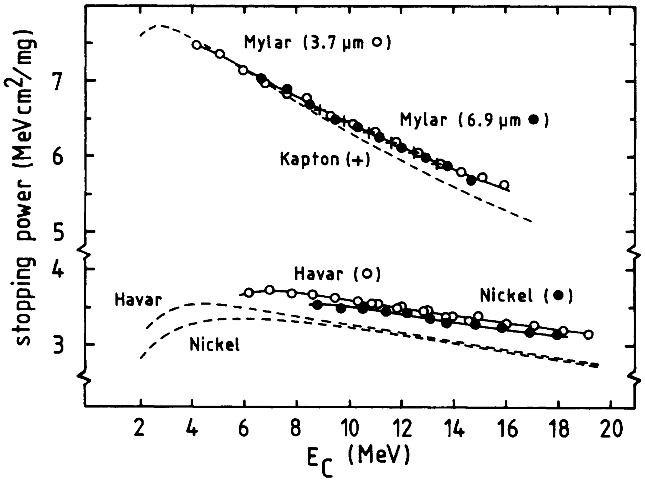

FIG. 1. Stopping powers of ^{12}C ions in Havar, nickel, Kapton, and Mylar. The solid curves have been fitted to the plotted experimental data to guide the eye. Calculated dashed curves indicate predictions obtained by using Bragg's rule in conjunction with scaled (Ref. 11) proton stopping (Ref. 10).

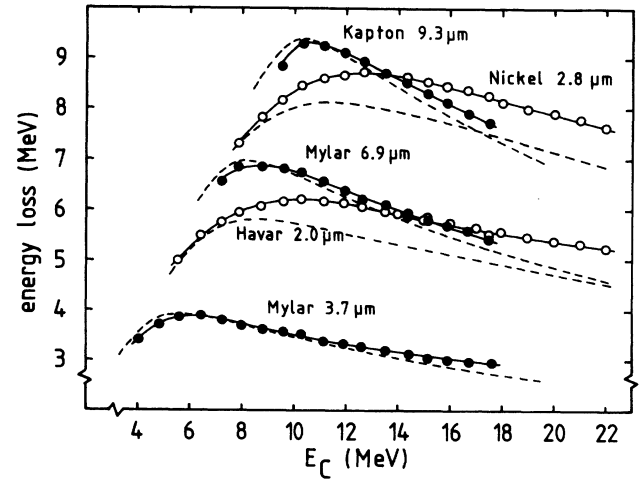

FIG. 2. Energy loss of ^{12}C ions in the foils given in Table II. Solid and dashed curves as in Fig. 1.

the response of the Si detector.[12] This effect was measured without the foil by dividing the detected energy differences ΔE_1, of the backscattering gold signals by the corresponding channel intervals ΔN. The result is illustrated in Fig. 3. The horizontal bars give the magnitudes of the energy differences and the vertical bars indicate the maximum experimental error due to uncertainties in signal positions. A similar general behavior is observed as in the cases of α particles[13,14] and ^{16}O ions.[9] An almost constant energy dependence of particle energy per channel at the higher particle energies is observed. But below 2 MeV ΔE_1 per channel increases slightly being 3% higher at 1 MeV than at 3 MeV. A titanium target was used below $E_1 = 6$ MeV to scatter the carbon ions.

Havar and nickel foils were found durable enough to be interposed into the direct beam from the accelerator. This arrangement was employed to provide an independent test of our Havar and nickel data. In this way a higher ion energy penetrating the foils than in the usual setup was also attained thus extending the energy interval of the energy-loss values up to 18–22 MeV. In Table II the data points above 14 MeV at exact MeV values correspond to this complementary method. Figure 2 shows good consistency in the energy-loss data determined by using the two alternative methods.

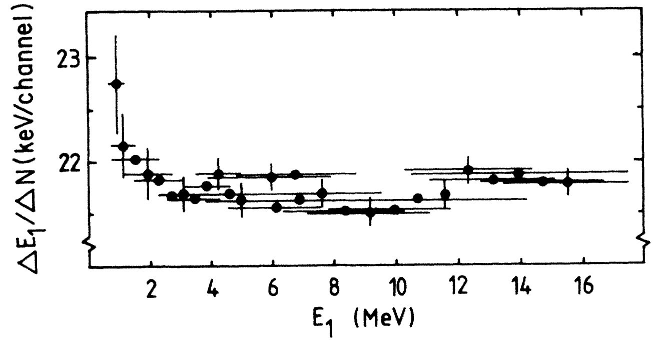

FIG. 3. Particle energy per channel as a function of energy of ions incident on a standard silicon surface barrier detector.

IV. DISCUSSION

Different from our earlier studies with ^{4}He and ^{16}O ions,[8,9] the present ^{12}C-ion stopping powers in the metal foils show a remarkable discrepancy when compared to calculated predictions obtained by using Bragg's rule and the Andersen-Ziegler parameters for proton stopping with scaling for carbon ions. According to Fig. 1, we suggest 10–12% higher stopping in Havar between 6 and 19 MeV, and 7–10% higher stopping in nickel be-

TABLE II. The energy loss ΔE of 3.98–22-MeV ^{12}C ions in Havar, nickel, Kapton, and Mylar foils.

	ΔE (MeV) in				
E (MeV)	Havar (2.00 μm)	nickel (2.75 μm)	Kapton (9.27 μm)	Mylar (3.73 μm)	Mylar (6.86 μm)
22.00	5.26±0.10	7.66±0.10			
21.00	5.34±0.10	7.77±0.10			
20.00	5.42±0.10	7.89±0.10			
19.00	5.47±0.10	8.01±0.10			
18.00	5.62±0.10	8.11±0.10			
17.52	5.50±0.10	8.24±0.10	7.76±0.10	2.93±0.10	5.40±0.10
17.00	5.64±0.10				
16.72	5.58±0.10	8.38±0.10	7.95±0.10	2.97±0.10	5.57±0.10
16.00	5.74±0.10				
15.93	5.68±0.10	8.46±0.10	8.14±0.10	3.01±0.10	5.69±0.10
15.13	5.78±0.10	8.57±0.10	8.32±0.10	3.07±0.10	5.81±0.10
15.00	5.82±0.10				
14.33	5.89±0.10	8.64±0.10	8.53±0.10	3.14±0.10	5.96±0.10
14.00	5.93±0.10				
13.54	5.97±0.10	8.70±0.10	8.71±0.10	3.21±0.10	6.09±0.10
12.74	6.06±0.10	8.70±0.15	8.93±0.10	3.28±0.10	6.21±0.10
11.95	6.13±0.15	8.64±0.15	9.10±0.15	3.34±0.10	6.39±0.15
11.15	6.16±0.15	8.58±0.20	9.24±0.20	3.40±0.10	6.54±0.15
10.35	6.21±0.15	8.45±0.25	9.32±0.25	3.52±0.10	6.72±0.15
9.56	6.13±0.15	8.13±0.25	8.86±0.30	3.54±0.10	6.80±0.20
8.76	6.04±0.20	7.82±0.30		3.62±0.15	6.85±0.25
7.96	5.95±0.20	7.32±0.30		3.72±0.15	6.85±0.30
7.17	5.75±0.25			3.82±0.20	6.54±0.30
6.37	5.51±0.25			3.89±0.20	
5.57	4.98±0.30			3.84±0.25	
4.78				3.71±0.30	
3.98				3.42±0.30	

tween 9 and 18 MeV, than the calculated predictions indicate. On the other hand, the results for the light composite foils follow the predictions in the lower end of our energy interval but increasingly exceed the calculations as the energy increases. Maximum deviations detected are 3% and 5% for Kapton and Mylar, respectively. In our previous studies quoted above, the maximum differences between experiments and calculations were observed for the light composite foils, whereas there was no distinct disagreement for the metal foils. ^{14}N stopping[7] indicated a less systematic behavior.

Comparison of our ^{12}C-ion data with previous experiments in nickel is presented in Fig. 4. Although it has been a little difficult to extract data accurately from the graphs published, a fair agreement between our values and those of Ved'manov *et al.*[3] is obvious from the figure. The data of Roll and Steigert[4] fall more than 10% below the smoothly connected curves plotted from the two other sets of measurements.

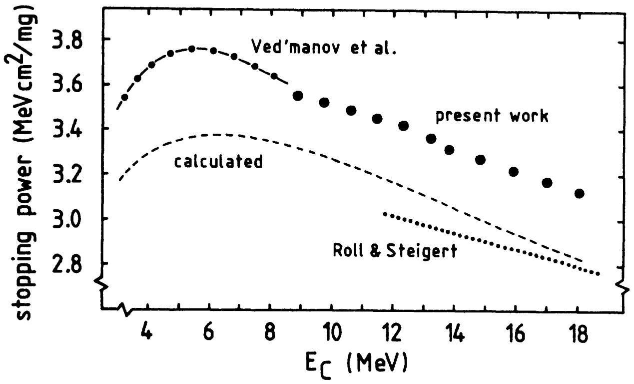

FIG. 4. Comparison of available experimental ^{12}C-ion stopping data in nickel within the energy range 4–18 MeV. The calculated dashed curve as in Fig. 1.

For ^{12}C ions in Mylar, the lack of exact data in Ref. 1 in the common energy interval renders quantitative comparison with our data impossible. No other experiments for any of the foils studied in this work are found in the literature.

In our energy range only the values of Anthony and Lanford[15] were found for carbon ions in solids. The results indicate that C-ion stopping powers in both low-Z and high-Z elemental matter may be well predicted by the scaling law assuming a Z_1^2 stopping power dependence on projectile velocity. For medium-Z elements the scaling is less successful. In particular, they demonstrate that the C-ion stopping in carbon above 15 MeV may be obtained by the scaling law. Our measurements support these systematics. As far as we know, however, the C-ion stopping powers in solid hydrogen, nitrogen, or oxygen have not been experimented. The differences between the present data and the scaling law predictions for the light composite foils of Mylar and Kapton may thus be attributed either to Bragg's rule violations or, less probably, in the light of the systematics mentioned above, to the nonpredictable C-ion stopping powers of the elements H, N, or O. In the case of the Ni and Havar foils our data significantly exceed the values predicted by scaling. In Ref. 15 similar behavior of C-ion stopping powers in copper above 15 MeV has been observed. As Havar consists mainly of medium-Z elements Cr, Fe, Co, and Ni, the nonpredictable stopping powers of the elements alone could explain the higher experimental values detected in the present work.

The stopping-power values obtained for Mylar by the 3.8-μm and 6.9-μm thick foils differ about 1% at maximum, but no systematical differences were observed. Thus effects like charge-change events[16,17] were not observed under the present experimental accuracy. Significantly thinner foils would therefore be needed to detect such minor effects. A brief consideration of these phenomena has been given in our earlier studies.[7,9]

To conclude, tabulations of ^{12}C-ion stopping in Havar, nickel, Kapton, and Mylar, based on experiments carried out in transmission geometry have been presented. These new data indicate about 10% higher stopping in the case of the metal foils than the calculated predictions indicate.

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