Nuclear Instruments and Methods 178 (1980) 523–530

STOPPING POWER VALUES OF Be, C, Al AND Si FOR ^{4}He IONS

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Received 23 February 1980

Absolute stopping values for ^{4}He ions in Be, C, Al and Si were measured over the energy region 200–2000 keV. Surface barrier particle detectors were used to measure changes in energy of ^{4}He ions after traversing thin, self-supported films. All parameters involved in these measurements were examined, controlled and cross checked, to give a consistent set of stopping values with estimated errors of 4%. Our results are compared with several published semiempirical tabulations of stopping data.

1. Introduction

The increasing use of accelerated ^{4}He beams as probes for the analysis of surface layers and characterization of multi-layer film structures has led to the need for more accurate stopping cross-section data.

A recent survey of stopping powers for ^{4}He ions [1] shows that there are wide discrepancies in measured stopping values, particularly at energies below 2 MeV. Disagreement amongst previously published results implies that difficulties existed that had not been recognized or that had not been adequately treated. Since the energy loss of charged particles travelling through matter is complicated by the charge exchange process taking place as the ions slow down in the medium, it is unlikely that theory can be used to resolve the discrepancies.

There are a number of comprehensive data tables which list semiempirical values of stopping cross sections derived from experimental measurements and theory. Examples of such tables are those of Williamson et al. [2], Bichsel and Tschalaer [3], Northcliffe and Schilling [4], Ziegler and Chu [5] and Ziegler [1]. The use of values from the tabulations has been helpful in many experiments, but it has been impossible to assign errors to the values used. Experiments which involved the use of stopping values gave results and conclusions which depended on the source of values chosen.

The two general methods used for determining stopping powers are; measuring the energy loss of a monoenergetic particle beam after transmission though a thin film, or determining the energy of particles scattered back from a surface layer of a thick target. The former permits a straightforward evaluation of experimental data, the main difficulty is in the preparation and characterization of the thin, self-supported films. The latter, or backscattering method, simplifies target preparation but characterization of contaminants and thickness is still a problem. In addition, the extraction of stopping values from backscattering data is complex [6].

We have undertaken a systematic study of stopping powers of heavy ions in a variety of solids, i.e. one laboratory using one consistent method for a series of projectile and target combinations. Emphasis was placed on cross checking the techniques and results to minimize systematic errors and make a good estimate of the magnitude of random errors. In our work, energy loss measurements were made by a transmission type experiment and film thicknesses were determined by weighing. Both of these factors were considered more likely to yield precise values. The present paper describes our measurements for ^{4}He ions in Be, C, Al and Si.

2. Experimental

2.1. Thin films

Films of Be, C, Al and Si were prepared by vacuum deposition onto suitable substrates [7] and were transferred by floating in water. The films were mounted on preweighted Ti frames (1.5 × 2.2 cm) with a "self-supported" opening of 9 mm diameter. The use of 0.13 mm thick Ti frames had the advantage of strength with minimum weight and showed no change in weight when dried after immersion in water. Film areas (~1.3 × 1.3 cm) were measured with a travelling microscope and film weights with a microbalance. Direct weighing of a known film area gave the areal density ($\mu g/cm^2$) and required no knowledge of densities in thin film formation. The thickness of every film used was determined individually since films prepared in the same batch often differed by 6 to 10%. Values ranged from 78 to 121 $\mu g/cm^2$ for Be, 28 to 128 $\mu g/cm^2$ for C, 53 to 188 $\mu g/cm^2$ for Al, and 123 to 182 $\mu g/cm^2$ for Si. These same foils were also used to measure the energy loss of α particles from radioactive sources [8]. Representative films from each batch prepared were analyzed for impurities by ^{4}He backscattering analysis [8]. Since films of Be, Al and Si readily form oxides during vacuum deposition, it was considered essential to select batches of films with no significant contamination by oxide formation, carbon deposits or incomplete removal of the release agent. Various positions of a foil were examined over an 8 mm × 8 mm area using a 2 mm diameter ^{4}He beam. The films were observed to be homogeneous (±1 $\mu g/cm^2$) since the energy difference measured between backscattering from front and back surfaces of a film was a constant.

2.2. Stopping measurements

The experimental arrangement used is shown in fig. 1. Beams of ^{4}He ions were obtained from a 2.5 MV Van de Graaff [9] and a 2 MV Pelletron [10] accelerator. As will be seen later, it was important to know the precise energy of beams used, consequently all energies were based on magnetic field settings as given by an NMR gaussmeter for the Van de Graaff and a Rawson rotating coil gaussmeter for the Pelletron. The magnetic field of each accelerator analyzing magnet was calibrated for 1.881 MeV protons with the ^{7}Li(p,n) reaction.

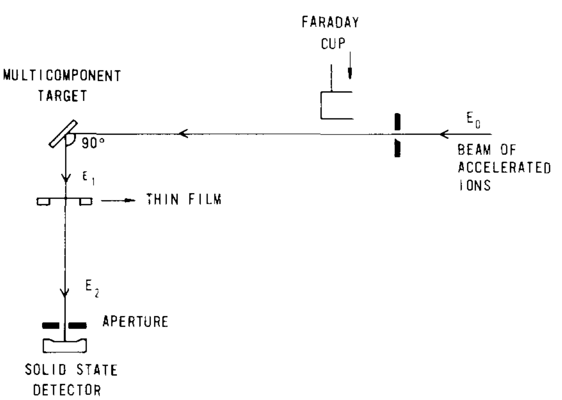

Fig. 1. Schematic of the experimental arrangement for measuring the energy loss of ^{4}He ions transmitted through thin films.

A monoenergetic beam of E_0 was collimated to 2 mm in diameter and allowed to strike a multicomponent target consisting of an evaporated layer of either Al (1.7 $\mu g/cm^2$) or Cr (2.2 $\mu g/cm^2$) together with Au (0.32 $\mu g/cm^2$) on carbon substrates. The incident beam scattering at a fixed angle off each component in the target produces several different but well defined energies E_1 and in addition reduces the beam intensity to an acceptable level for detection. From the kinematics factors for scattering at 90° from Al, Cr and Au, data collected at a given accelerator energy simultaneously provided stopping values at several different but known energies.

An energy spectrum of He ions scattered from a multicomponent target is shown in fig. 2. When a film is inserted the peaks move to lower energies. A measure of the energy shift divided by the film thickness gives stopping values at those energies. By using a reduced intensity scattered beam, no deterioration in the quality of films was observed due to beam heating, sputtering, or extraneous depositions.

Up to 11 films of different thicknesses and different elements were mounted on a rotating wheel inside the vacuum system. A blank position on the wheel allowed the measurement of unshifted peak positions. The energies of scattered ^{4}He beams before and after transmission through each film were measured with a surface barrier particle detector [11] fitted with a 3 mm diameter aperture. The detector subtended a half angle of 1.9° at the multicomponent target and had a resolution of 16 keV fwhm for 1 MeV ^{4}He ions. To minimize distortion in the shapes of backscattered peaks, the detector system was operated with a pulse pile-up rejector system. Energy spectra were recorded in a pulse height analyzer with a gain of 5 keV per channel and were transferred to a large computer via magnetic tape for centroid peak fitting. Films were prepared thin enough to minimize distortion in peak shapes due to excessive energy straggling.

Energy calibration of the detector system was achieved by using ^{4}He beams of precisely known energies, as defined by the magnetic field of the

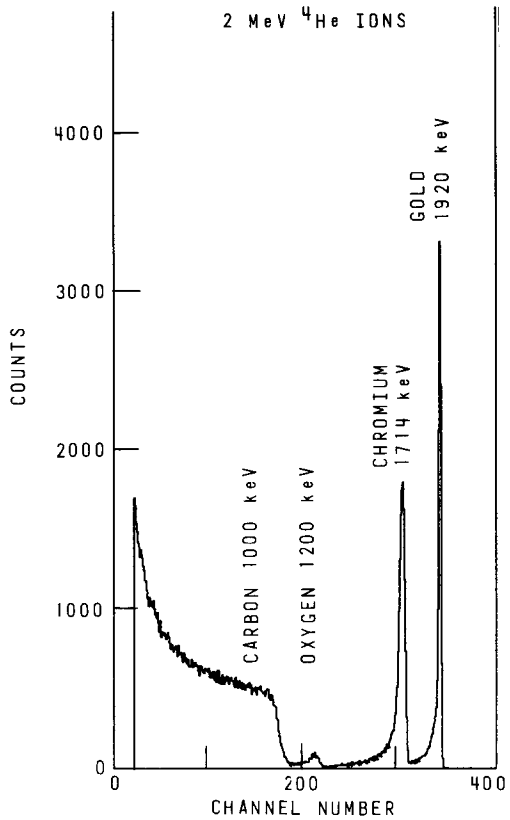

Fig. 2. Energy spectrum of ^{4}He ions scattered at 90° from a thin evaporated surface layer of Cr and Au on a thick carbon substrate. The incident ^{4}He energy was 2 MeV.

accelerator analyzing magnets. In this way corrections were included for effects due to detector window thickness and any nonlinear energy response of the detector system to ^{4}He ions. As expected, field values set for 2 MeV singly charged ^{4}He or doubly charged ^{4}He ions produced an identical energy, as measured by the particle detector. Frequent measurements of beam energies without foils indicated that a well appertured beam was stable to ±2 keV.

Incident ^{4}He beam energies from 300 to 2200 keV were used to obtain stopping values at energy intervals no greater than 50 keV over the entire energy range.

3. Results

The stopping power for energetic ions in matter is usually treated as the sum of two independent contributions, the elastic or nuclear part and the electronic part. Since we are unable to separate the two components experimentally, total stopping powers are determined.

Stopping values of Si for ^{4}He ions are plotted in fig. 3. Each value is based on an observed energy loss due to a film of measured thickness and is plotted at the average energy, i.e. the initial energy minus half the observed energy shift. The uncertainty in the average energy varied from 5 keV at 200 keV to 20

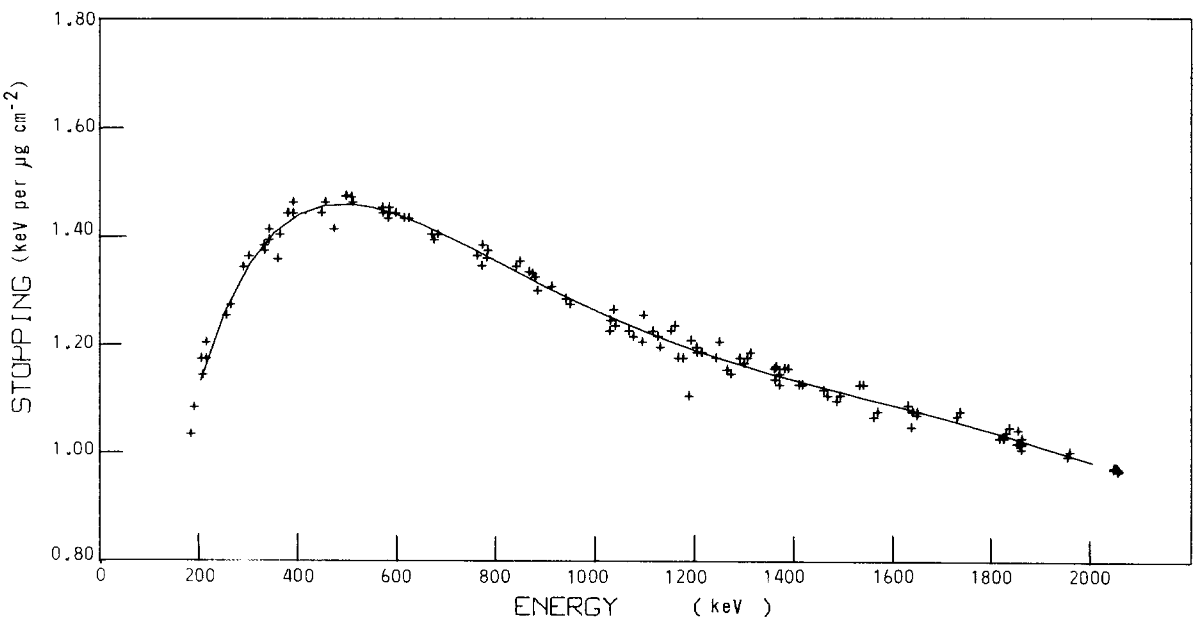

Fig. 3. Stopping values of Si for ^{4}He ions: +, measured values; the full curve, least squares polynomial fit.

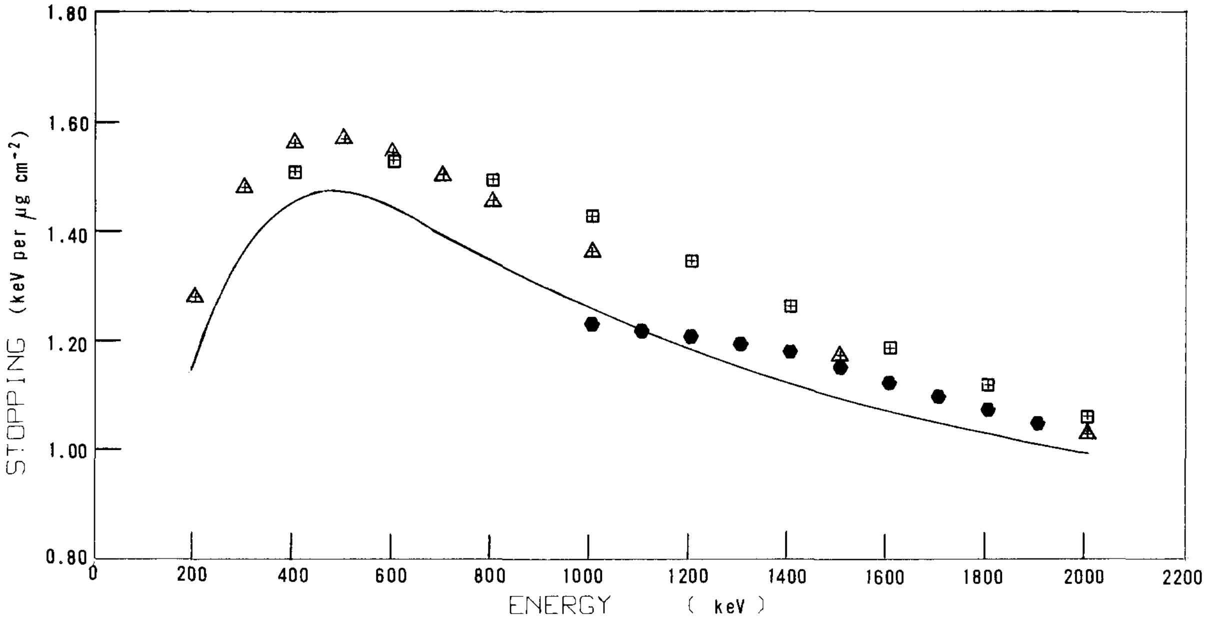

Fig. 4. Comparison of measured stopping values with semiempirical tabulations for ^{4}He ions in Si: •, Bichsel and Tschalaer [3]; ⊞, Ziegler and Chu [5]; ⍋, Ziegler [1]; full curve, this work.

keV at 2 MeV. The experimental error for any of our stopping measurements consisted of peak fitting to ±0.2 channels (0.5–1.5%), detector energy calibration and stability (0.2–1%), film weighing to ±2 μg (0.8–3%), and film area determination (2–3.5%). There were 116 individual stopping measurements for

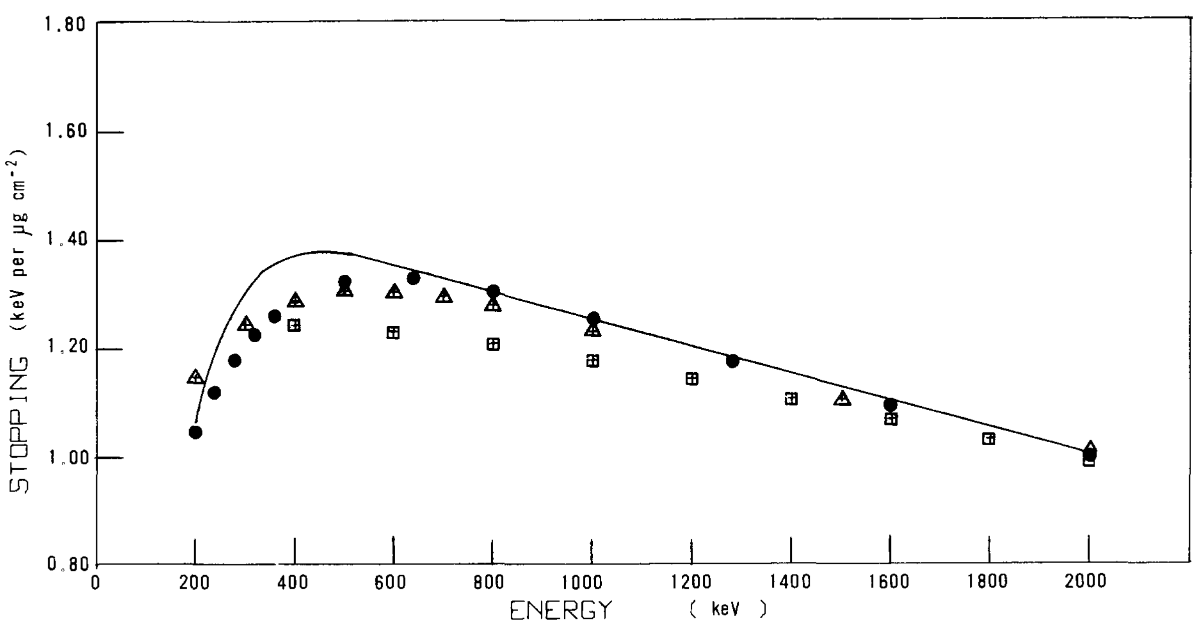

Fig. 5. Comparison of measured stopping values with semiempirical tabulations for ^{4}He ions in Al: •, Northcliffe and Schilling [4]; ⊞, Ziegler and Chu [5]; ⍋ Ziegler [1]; full curve, this work.

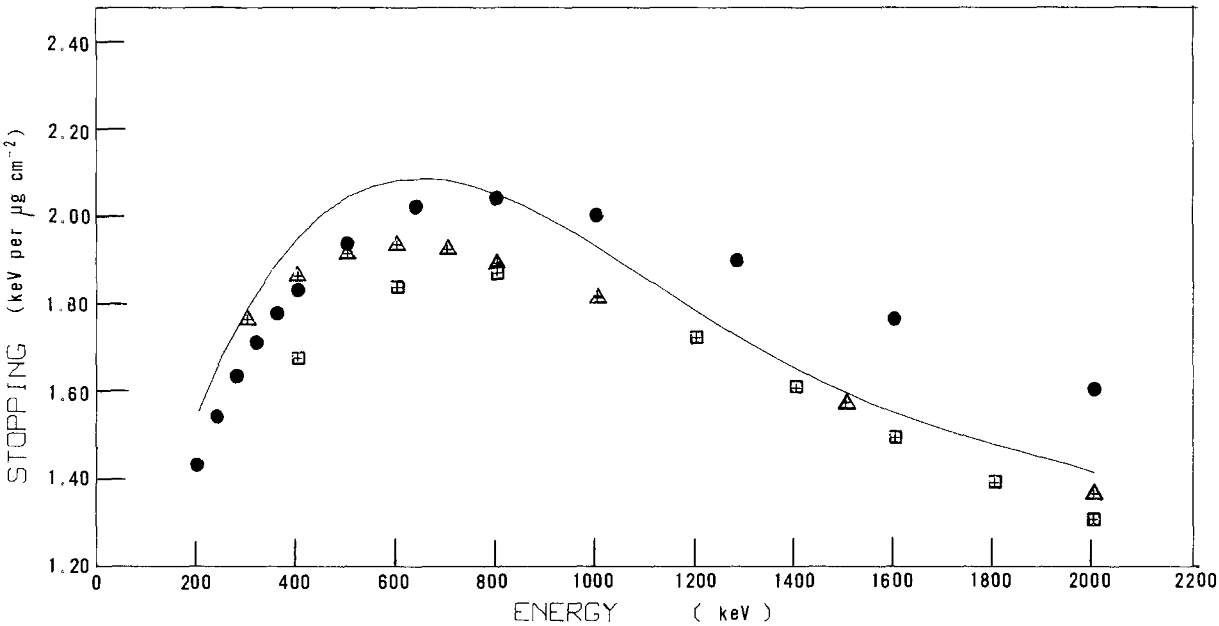

Fig. 6. Comparison of measured stopping values with semiempirical tabulations for ^{4}He ions in C: •, Northcliffe and Schilling [4]; ⊞, Ziegler and Chu [5]; ⚠, Ziegler [1]; full curve, this work.

Si. The maximum observed spread in values for a series of films at a given energy was less than 7%. A smooth curve drawn through the data points was based on a least squares polynomial fit and is shown as the solid curve, which has an estimated error of 4%.

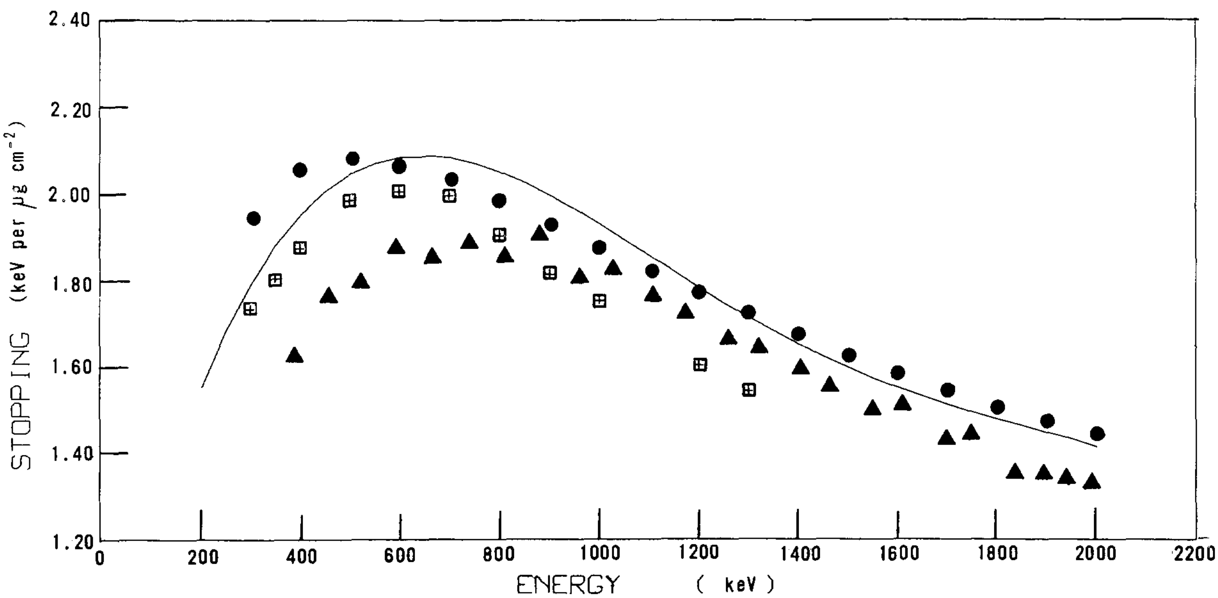

Fig. 7. Comparison of measured stopping values of carbon for ^{4}He ions: ⊞, Porat and Ramavataram [13]; ▲, Chu and Powers [14]; •, Matteson et al. [12]; full curve, this work.

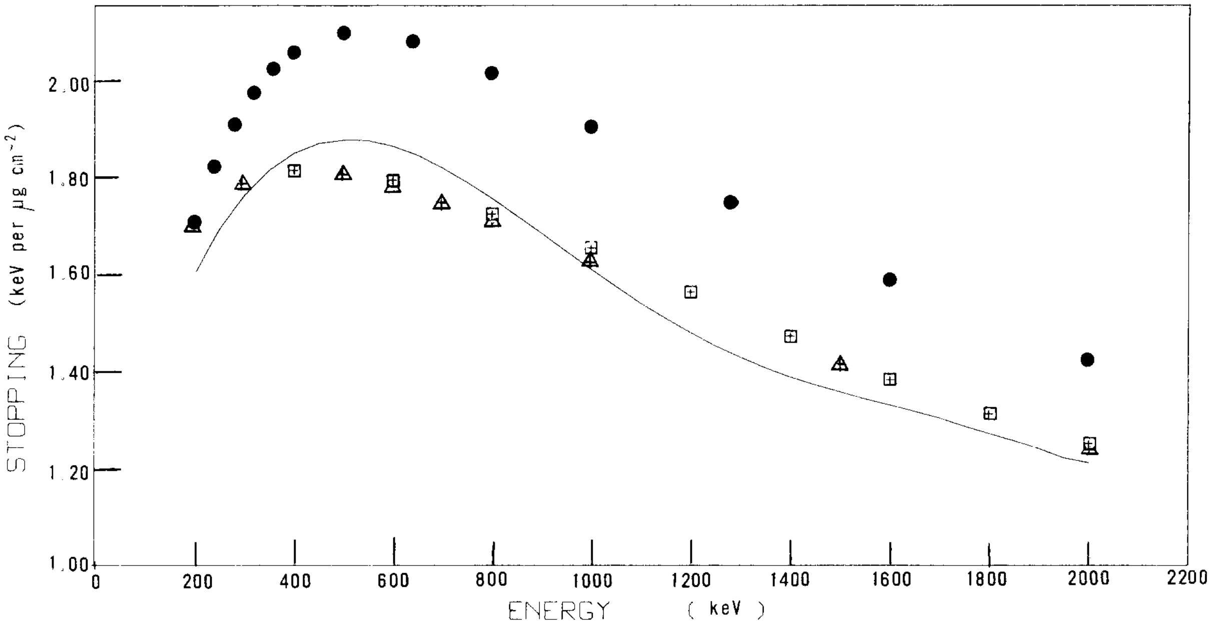

Fig. 8. Comparison of measured stopping values with semiempirical tabulations for ^{4}He ions in Be: •, Northcliffe and Schilling [4]; ⊞, Ziegler and Chu [5]; ⚠, Ziegler [1]; full curve, this work.

In general, graphs become cluttered when trying to compare our individual measurements of stopping values with those of other investigators. Since Ziegler [1] had already plotted comparisons of previous measurements we elected to present our data as smooth curve fits and make comparisons with values from semiempirical tabulations. This seem reasonable since the latter are used rather than individual values from a particular measurement. In fig. 4 our Si data, shown as the solid line least squares fit, is compared with values from semiempirical tabulations. Although the suggested value from Ziegler and Chu [5] at 1 MeV is 13% higher than our measurement, Ziegler's [1] newest estimate at that energy is only 7% higher. The older tabulated values by Bichsel and Tschalaer [3] give reasonable agreement with our data over a comparable energy region.

Our stopping measurements for ^{4}He in Al consisted of 153 separate measurements which are summarized in fig. 5 as the solid curve least squares fit, together with semiempirical values for comparison. This time the Ziegler and Chu value [5] at 1 MeV is 7% lower than ours, while Ziegler's value [1] is 2% lower. However, Ziegler and Chu are as much as 12% lower at 600 keV. Above 1 MeV the Northcliffe and Schilling values [4] are similar to ours. In the energy range 1.4–1.6 MeV there is good agreement among all the semiempirical tabulations considered and the present measurements.

The corresponding graph for the stopping of ^{4}He in carbon is shown in fig. 6 and was based on 206 separate measurements. Note that at 2 MeV the value suggested by Ziegler and Chu [5] differs by 20% from that given by Northcliffe and Schilling [4]. It was discrepancies such as these that motivated the present study. At 2 MeV the stopping values of Northcliffe and Schilling [4] is 14% higher, while Ziegler and Chu [5] and Ziegler [1] are 8% lower than our measurements. In the case of carbon, a comparison of experimentally measured values in the energy region below 2 MeV is shown in fig. 7. There would appear to be good agreement between our values and those of Matteson et al. [12] at energies above 600 keV. However, the values given by Matteson are for bulk graphite, which were said to be 6–28% higher than the corresponding values for vapor-deposited carbon, the difference being attributed to an allotropic effect. In view of these results the question is still unanswered as to whether allotropic effects influence stopping powers.

The results of 114 measurements of ^{4}He ions in Be are shown as the solid curve least squares fit in figure 8. Northcliffe and Schilling values [4] are higher than our measured values, 15% at 2 MeV,

Table 1
Stopping power values for ^{4}He ions (keV per μg cm^{-2}) a)

Energy (keV)	Stopping materials			
	Be	C	Al	Si
200	1.60	1.55	1.07	1.15
250	1.69	1.68	1.21	1.23
300	1.76	1.79	1.30	1.35
350	1.81	1.88	1.35	1.41
400	1.85	1.95	1.37	1.45
450	1.87	2.00	1.38	1.46
500	1.87	2.04	1.37	1.47
550	1.87	2.07	1.36	1.46
600	1.86	2.08	1.34	1.44
650	1.84	2.08	1.33	1.41
700	1.81	2.08	1.32	1.39
750	1.78	2.06	1.31	1.37
800	1.75	2.04	1.30	1.35
850	1.72	2.02	1.28	1.32
900	1.68	1.99	1.27	1.30
950	1.64	1.96	1.26	1.28
1000	1.61	1.93	1.24	1.26
1050	1.57	1.89	1.23	1.23
1100	1.54	1.85	1.21	1.21
1150	1.51	1.82	1.20	1.20
1200	1.48	1.78	1.19	1.18
1250	1.45	1.74	1.18	1.16
1300	1.43	1.71	1.17	1.15
1350	1.41	1.68	1.16	1.13
1400	1.39	1.65	1.15	1.12
1450	1.37	1.62	1.13	1.11
1500	1.36	1.59	1.12	1.09
1550	1.34	1.57	1.11	1.08
1600	1.33	1.55	1.10	1.07
1650	1.32	1.53	1.09	1.06
1700	1.30	1.51	1.08	1.05
1750	1.29	1.49	1.06	1.04
1800	1.27	1.47	1.05	1.03
1850	1.25	1.46	1.04	1.02
1900	1.24	1.44	1.02	1.01
1950	1.22	1.43	1.01	1.00
2000	1.21	1.41	1.00	0.990

a) Obtained by drawing smooth curves through the experimental data.

whereas the values given by Ziegler and Chu [5] and Ziegler [1] are in reasonable agreement with our data, 3.2% lower at 2 MeV but as much as 7% lower at 1.4 MeV.

A summary of our stopping values for ^{4}He ions in Be, C, Al and Si is given in table 1. Because of the large amount of data taken, its presentation was simplified by performing a least squares polynomial fit to obtain best values at 5 keV intervals. Since stopping values do not change rapidly with energy, values are listed at 50 keV intervals.

It should be mentioned that under our experimental conditions, no evidence was seen for a thickness dependence of stopping values.

4. Discussion

There have been no technological advances which would make recent stopping power measurements more reliable than those made a decade ago. Thus it is difficult to understand the reason for poor agreement amongst the results from different investigators, as shown by Ziegler [1].

We have completed measurements for the stopping of ^{4}He ions in some light element targets over the energy range which appears to be the most difficult [1]. In our work emphasis was placed on simplicity of method, thereby eliminating the added uncertainties which might be introduced by using more complex techniques. In order to establish validity, measurements were repeated over and over under the same conditions, then again under different conditions, i.e., different film thicknesses and a different accelerator with an independent energy calibration system. Stopping values were also cross-checked by cycling films of different elements under the same experimental conditions. Measurements of absolute stopping values were made with an estimated error of 4% and have been plotted for comparison with values from semiempirical compilations. This enables the reader to judge whether a particular previous experiment which used stopping powers from a tabulation, would be expected to give different results if renormalized to our recent data.

As mentioned previously, semiempirical tabulations have been useful in the past. Each successive publication, based on more accumulated data, often gave different values. The most recent ^{4}He compilation by Ziegler [1] gave values which are within 5 to 10% of our measured stopping values for the elements Be, C, Al and Si.

Stopping measurements are being continued by studying other projectile–target combinations.

We would like to thank others at CRNL who made this work possible: J.L. Gallant and D.J.P. Yaraskavitch for the preparation of high quality thin films, also G.A. Sims, G.R. Bellavance and J. Lori for operating the accelerators under rather stringent conditions.

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