Stopping Cross Sections in Boron of Low Atomic Number Atoms with Energies from 15 to 140 keV *

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Dedicated to Prof. J. MATTAUCH *on his 70th birthday*

The electronic stopping cross sections in boron for atomic projectiles with $Z \leqq 11$ have been determined in the energy interval 15 to 140 keV. Reasonable agreement is found with theory, however the previously observed periodic dependence of S_ε on the atomic number of the projectile is also evident. Results for the relative straggling in energy loss are reported for hydrogen projectiles in boron, carbon, and aluminium targets and for helium projectiles in boron and carbon. Theoretical straggling estimates agree reasonably well with the experimental results.

The penetration of atomic projectiles with keV energies through solid films has been a matter of experimental study in this laboratory beginning with the work of VAN WIJNGAARDEN and DUCKWORTH [1]. Since that time, systematic atomic stopping cross sections have been determined in carbon and aluminium by the work of ORMROD and DUCKWORTH [2] and ORMROD et al. [3].

These last two papers will be designated II and III, respectively, in the following discussion. The present work extends the systematic stopping cross section data to boron targets.

In traversing matter, an atomic projectile loses energy both to electrons in the stopping medium and to recoiling atoms. Thus, the total stopping cross section is the sum of an electronic component (S_ε) and a nuclear component (S_ν), with the latter increasing in importance at lower velocities. Using THOMAS-FERMI arguments, LINDHARD et al. [4] have derived the following expression for the electronic stopping cross section applicable for particle velocities below $v_0 Z_1^{2/3}$:

$$S_\varepsilon = \xi_\varepsilon \, 8 \pi \varepsilon^2 a_0 Z_1 Z_2 (Z_1^{2/3} + Z_2^{2/3})^{-3/2} (v/v_0) \quad (1)$$

where ε is the elementary charge, a_0 and v_0 are the radius and velocity of an electron in the first BOHR orbit of hydrogen, Z_1 and Z_2 are the atomic numbers of the projectile and target atoms, respectively, v is the projectile's velocity, and ξ_ε is a constant lying between 1 and 2 which may vary as $Z_1^{1/6}$.

A nuclear differential cross section has also been derived by LINDHARD et al. [4] and this has been used in II and III and in the present work to correct our experimental results for the small nuclear contribution to the total energy loss. Thus our experimental results lead to electronic stopping cross sections which can be compared to eq. (1).

We have found that our experimental data can be expressed by the following empirical relation:

$$S_\varepsilon = k \, E^P \quad (2)$$

where the coefficient k and exponent P are determined independently for each projectile-target combination.

When initially-monoenergetic projectiles pass through matter, a distribution in energy arises amongst them because the various particles undergo different numbers of collisions and the energy transfer per collision is different for different events. This energy distribution is commonly called the straggling of the projectiles, and the comparison of the energy distribution with the energy loss is called the relative straggling. Using a degenerate electron gas model, LINDHARD [5] has derived the following expression for

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1 A. VAN WIJNGAARDEN and H. E. DUCKWORTH, Can. J. Phys. **40**, 1749 [1962].

2 J. H. ORMROD and H. E. DUCKWORTH, Can. J. Phys. **41**, 1424 [1963].

3 J. H. ORMROD, J. R. MACDONALD, and H. E. DUCKWORTH, Can. J. Phys. **43**, 275 [1965].

4 J. LINDHARD, M. SCHARFF, and H. E. SCHIØTT, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **33**, No. 14 [1963].

5 J. LINDHARD, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **28**, No. 8 [1954].

the relative straggling of a beam of atoms losing energy to electronic processes in a solid:

$$\Omega^2/\Delta E \approx [5\, m\, v^2\, \hbar\, \omega_0]^{1/2} \qquad (3)$$

where Ω is the standard deviation of the energy distribution, ΔE is the most probable energy loss, $\hbar$ is PLANCK's constant divided by 2π, m is the electron mass, v is the particle velocity, $\omega_0 = (4\pi\varepsilon^2 n_\varepsilon/m)^{1/2}$ is the electron resonance frequency of the degenerate electron gas, and n_ε is the electron density.

Substitution of the known values of the constants into eq. (3) gives the relative electronic straggling as:

$$\Omega^2/\Delta E \approx 3.2 \times 10^{-16}\, n_\varepsilon^{1/4}\, v \qquad (4)$$

where both Ω and ΔE are expressed in keV. Eq. (4), which predicts that the relative electronic straggling is independent of film thickness, may be compared directly to our experimental results for hydrogen and helium projectiles because nuclear collisions do not play a large role in the stopping of these particles at keV energies.

1. Experimental

The targets used in these experiments were boron films ranging in thickness from 2 to 60 μg/cm^2. Films thicker than about 20 μg/cm^2 were self-supporting, while the thinner films were mounted on 1000 line per inch nickel mesh which allowed 49% transmission. Experiments done with both types of mounting gave similar results. Following the work in II, the thickness of each films was determined by comparing the energy loss of 30 keV protons with the proton stopping cross section curve shown in Fig. 1. This curve was established relatively using the energy loss of protons in thin films, and absolutely using the energy loss of protons in thick weighed films. The probable error in the film thickness determined in this manner was 4%.

The boron films were vacuum deposited on glass microscope slides and were later stripped from the slides in distilled water. Evaporation of boron was accomplished using a modification of the techniques of MUGGLETON and HOWE [6] and ADAIR and KOBISK [7]. Electron bombardment heating was used to melt the tip of a boron pellet mounted on a water cooled copper anode. The power dissipation sufficient to cause evaporation was somewhat less than 100 watts and the time needed for deposition ranged from about 20 seconds for the thinnest to several minutes for the thickest films. The pressure in the system during an evaporation was about 5×10^{-6} torr.

Examination of the films by an electron microscope revealed that the films were amorphous and that the surfaces were extremely regular. The shape of the energy spectrum of 30 keV protons was used to judge the acceptability of a given film. Any asymmetry in the spectrum shape was attributed to irregularities across the film. Such films were discarded.

As the details of the experimental procedure were given in II, only a brief description will be provided here. The desired ions were selected in a ten-inch 90° magnetic spectrometer and the thin film target was situated near the focus of this spectrometer. Using a seven-inch 90° electrostatic analyser, the energy distribution of the emerging ions was determined from the ion counting-rate at each energy setting. The incident energy (E_{in}) was also determined with the electrostatic analyser after the film had been removed from the beam.

From each energy spectrum the following energies were determined:

E_{out} = the most probably energy of the emerging ions,
$\Delta E = E_{\text{in}} - E_{\text{out}}$ = the most probable energy loss,
$\bar{E} = (E_{\text{in}} + E_{\text{out}})$,
Ω_0 = the half width at half height.

The observed stopping cross section (S_0) at energy $\bar{E}$ is given by the following expression:

$$S_0 = (1/N)\,(\Delta E/t) \qquad (5)$$

where N is the atomic density, and t is the film thickness.

With a particular ion, S_0 was determined over as wide an energy range as possible. For singly-charged ions this range was from 15 to 70 keV. When doubly-charged ions were available, the energy range was extended to 140 keV.

With the lighter projectiles, the energy distributions were completely symmetric indicating that energy loss in nuclear collisions is negligible for projectiles emerging in the forward direction. As a result, the observed stopping cross section for these projectiles (hydrogen, helium, and lithium) is virtually equivalent to the electronic stopping cross section (S_ε).

[6] A. H. F. MUGGLETON and F. A. HOWE, Nucl. Instr. Methods **13**, 211 [1961].

[7] H. L. ADAIR and E. H. KOBISK, Trans. 9th National Vacuum Symposium, American Vacuum Society, 1962.

For the heavier projectiles, nuclear stopping competes with electronic stopping, particularly at low energies. However, for projectiles emerging in the forward direction, the electronic energy loss is still dominant in our experimental energy range. A Monte Carlo calculation, developed by ORMROD for the work done with carbon and aluminium targets (that is, II and III), was used to calculate the contribution of the nuclear energy loss to ΔE. The electronic stopping cross section was then found by subtracting the calculated nuclear contribution from the observed stopping cross section.

2. Results and Discussion

The electronic stopping cross sections for hydrogen stopping in boron are shown in Fig. 1. Proton results (shown as solid dots) are plotted directly as a function of E, while deuteron results (shown as open circles) are plotted with the energy scale contracted by a factor of two in order to compare the behaviour of the hydrogen isotopes at the same velocity. The probable error in the cross sections shown is 4%.

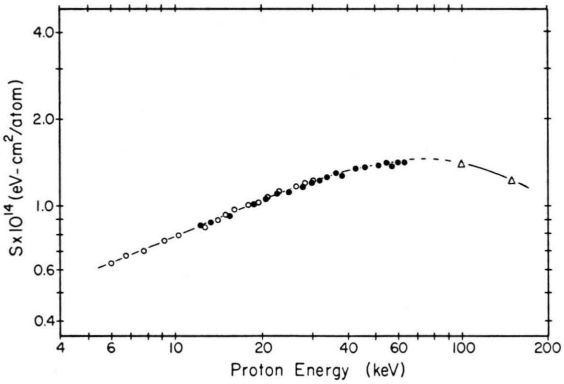

Fig. 1. Electronic stopping cross sections for ^{1}H (shown as solid dots) and ^{2}D (shown as open circles) projectiles in boron. The deuteron results have been plotted at half their actual energy. Experimental values of OVERLEY and WHALING [9] are shown as triangles.

At proton energies below 25 keV (at which energy $v = v_0$) the electronic stopping cross section can be represented by eq. (2), with an energy exponent $P = 0.40$. However, at higher energies, the results in Fig. 1 clearly show the transition in the energy dependence of S_ε towards the region in which the BLOCH [8] stopping formula is applicable. The experimental stopping cross sections of OVERLEY and WHALING [9] are shown as triangles at 100 and 150 keV in Fig. 1. These represent the only available comparisons with our results, and the dashed curve connecting the two sets of results suggests that they are in agreement.

Monte Carlo calculations were performed at 25 and 40 keV with neon projectiles stopping in boron; also, the previous calculations for neon stopping in carbon were extended in a manner similar to that described in II to obtain corrections in boron targets at 30 and 53 keV. These four Monte Carlo corrections for neon are shown in Fig. 2 along with the observed stopping cross sections and the theoretical nuclear stopping cross section from LINDHARD et al. [4]. The electronic stopping cross section was approximated by a straight line [eq. (2)] through the calculated points approaching S_0 asymptotically at higher energies. The asymptotic approach of S_ε to S_0 is dictated by the decrease in nuclear stopping at higher energies.

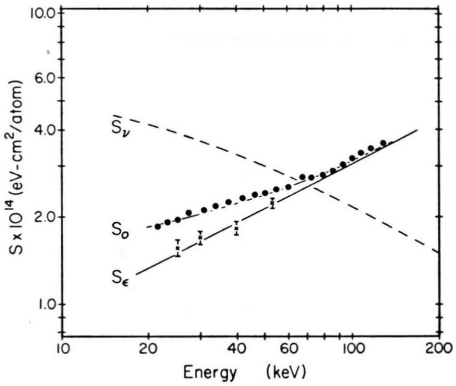

Fig. 2. Stopping cross sections $^{20}Ne \rightarrow B$. The crosses are the results of the Monte Carlo calculations.

For each projectile studied, the coefficients k and exponents P from eq. (2) are given in Table 1. The probable error in S_ε, determined from Table 1, varies from 4% for the light projectiles (where no correction was required) to about 9% for ^{23}Na. At the higher energies where the Monte Carlo corrections are smaller the probable errors are also slightly less. The experimental values of P range from 0.40 to 0.51 in much the same way as did our earlier results with carbon and aluminium targets; the value $P = 0.5$ is predicted from eq. (1).

[8] F. BLOCH, Ann. Phys. **16**, 285 [1933].
[9] J. C. OVERLEY and W. WHALING, Phys. Rev. **128**, 315 [1962].

Projectile	$k \times 10^{15}$ (eV—cm^2/atom)	P	Energy Range (ke V)
^{1}H	3.2	0.40	12— 25
^{4}He	3.6	0.42	15— 70
^{7}Li	2.4	0.47	15— 70
^{11}B	3.2	0.51	15—140
^{12}C	4.9	0.47	15—140
^{14}N	4.5	0.49	15—140
^{16}O	4.7	0.47	15—140
^{19}F	4.1	0.46	15—140
^{20}Ne	2.9	0.51	20—140
^{23}Na	2.7	0.46	25— 70

Table 1. Coefficients (k) and Exponents (P) for the Electronic Stopping Cross Sections in Boron as Expressed in the Equation $S_\varepsilon = k\,E^P$.

The variation of S_ε with the atomic number of the projectile (Z_1) is shown in Fig. 3, where S_ε has been plotted against Z_1 for a particle velocity of 9×10^7 cm/sec. This velocity has no particular significance, but it is the velocity at which comparisons of S_ε with Z_1 were made in carbon and aluminium targets. The

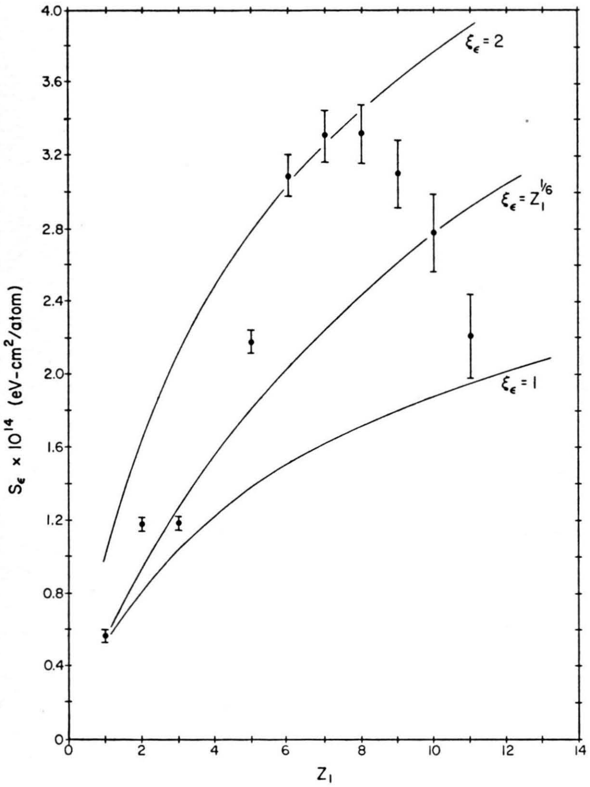

Fig. 3. Electronic stopping cross sections in boron as a function of projectile atomic number at constant velocity ($v = 9 \times 10^7$ cm/sec). The solid curves are the predictions of LINDHARD et al. [4] from eq. (1).

lines drawn on the graph in Fig. 3 are solutions to eq. (1): the central line corresponds to $\xi_\varepsilon = Z_1^{1/6}$, while the outside lines correspond to the limits of the theoretical prediction. The shape of the periodic dependence of S_ε on Z_1 is the same as that found with carbon and aluminium targets. Graphs similar to Fig. 3 have been made at other velocities in the experimental region. If there is any shift in the observed periodicity as the particle velocity is changed, our experiments are not sufficiently sensitive to reveal it.

The theory of LINDHARD et al. [4], with $\xi_\varepsilon = Z_1^{1/6}$ in eq. (1), predicts the general trend of the experimental results very well, but, as LINDHARD has emphasized, one would not expect a theory based on a statistical model to explain in detail variations that are associated with the periodic properties of the outer electrons in the atom.

As mentioned earlier, the fact that the energy lost by light particles is predominantly accounted for by electronic processes allows us to associate the width of the symmetric energy spectra (Ω_0) with the straggling in electronic energy loss. A small correction to Ω_0 was made to take into account the energy spread of the incident beam by assuming that:

$$\Omega^2 = \Omega_0^2 - W^2 \tag{6}$$

where Ω is the straggling caused by collision processes in the film and $W = E/350$ is an empirical estimate approximating the width of the incident beam at energy E. No correction was made for any component of Ω caused by variations in film thickness.

Any single determination of Ω was uncertain by greater than 20%. However, a technique was used by which more reliable results could be obtained. VAN WIJNGAARDEN and DUCKWORTH [1] found that $\Omega/\Delta E$ was constant for the same particle-film combination. From experiments at all energies, a mean value of $\Omega/\Delta E$ was obtained for a projectile stopping in a given film; then ΔE was determined at the required energy and the corresponding value of Ω was calculated. The probable error in the values of Ω so obtained ranged from 3% to 12%.

The straggling of hydrogen projectiles was determined in boron, carbon, and aluminium foils at a particle velocity $v = v_0$, (equivalent proton energy 25 keV). Fig. 4 shows Ω^2 plotted against ΔE for thirteen different boron targets. The relative straggling, to be compared with eq. (4), was determined from the slope of the best line through the experi-

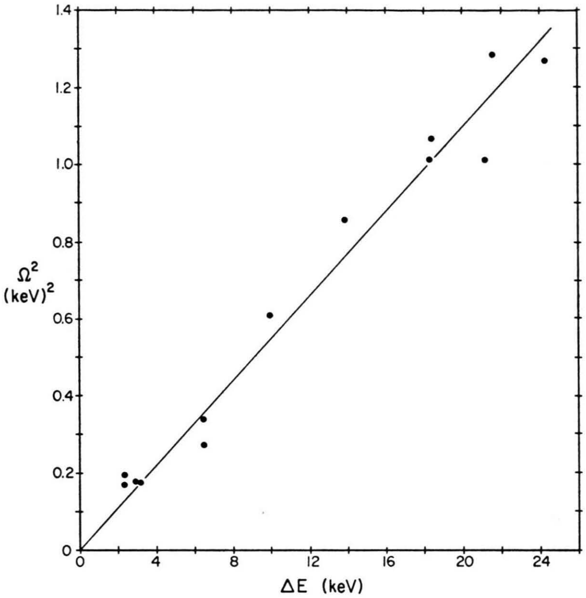

Fig. 4. The straggling of 25 keV protons ($v=v_0$) as a function of ΔE in boron films of various thicknesses. The slope of the solid line determines the relative straggling.

mental points. Ten of the thirteen points lie within one probable error of the line, and we conclude that the relative straggling is independent of film thickness in agreement with the theoretical prediction. Similar plots were made for carbon and aluminium targets and the relative electronic straggling for all three elements is shown in Table 2.

Relative straggling values for helium projectiles at 25 keV ($v = 0.5\ v_0$) in boron and carbon targets were also determined. A plot of Ω^2 versus ΔE was not possible because experiments with helium ions were performed with thin films only. But the relative straggling $\Omega^2/\Delta E$ was calculated, as before, from ΔE and the average value of $\Omega/\Delta E$.

In comparing the straggling predicted from eq. (4) and the experimental results, values of $\Omega^2/\Delta E$ were calculated using values of the electron density (n_ε) corresponding to:

(1) the atomic density (N)

(2) the electron density ($Z_2\, N$).

The experimental and calculated values of $\Omega^2/\Delta E$ are given in Table 2.

The agreement between experimental and calculated values for hydrogen straggling is good. Although the agreement found for helium straggling is not as good, it is quite reasonable in view of the approximate nature of eq. (4), and the somewhat greater nuclear contribution in helium than in hydrogen.

Straggling determinations were not carried out with the heavier projectiles because of the lower counting rates and increased nuclear stopping (giving rise to asymmetric energy distributions) with these ions.

3. Conclusion

Stopping cross sections have been determined in thin boron films for atomic projectiles ($Z \leqq 11$) with energies from 15 to 140 keV. General agreement was found with the predictions of LINDHARD et al. [4], however the same periodic dependence of S_ε on Z_1 was found as was found in earlier work with carbon and aluminium films.

The straggling in energy loss has been determined for 25 keV protons in boron, carbon, and aluminium films and for 25 keV helium projectiles in boron and carbon. The results have been compared with the theoretical analysis of LINDHARD [5] and reasonably good agreement exists.

Acknowledgements

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Projectile	Relative Electronic Straggling		Target: Boron	Target: Carbon	Target: Aluminum
Hydrogen at 25 keV	Experimental $\Omega^2/\Delta E$		0.055 $\pm$ 0.005	0.044 $\pm$ 0.005	0.078 $\pm$ 0.008
($v = v_0$)	Theoretical eq. (4)	$n_\varepsilon = N$	0.043	0.041	0.035
		$n_\varepsilon = Z_2\, N$	0.064	0.066	0.067
Helium at 25 keV	Experimental $\Omega^2/\Delta E$		0.054 $\pm$ 0.015	0.070 $\pm$ 0.021	
($v = 0.5\, v_0$)	Theoretical eq. (4)	$n_\varepsilon = N$	0.021	0.020	
		$n_\varepsilon = Z_2\, N$	0.032	0.033	

Table 2. Comparison Between Experimental and Theoretical Values of the Relative Electronic Straggling ($\Omega^2/\Delta E$).