Stopping Powers of Some Solids for 30–90-MeV ^{238}U Ions†

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Uranium ions of energies in the range 30–90 MeV from the Oak Ridge Tandem accelerator were used to measure stopping powers for C, Al, Ni, Ag, and Au foils. Foil thicknesses were determined by α-particle energy-loss measurements. The results are compared with various theoretical predictions. Subtraction of an assumed nuclear-stopping component leaves a residual electronic stopping power which is velocity proportional but does not appear to extrapolate to the origin, in disagreement with theory. Comparisons with other ions indicate that heavier ions exhibit larger discrepancies with theory in that the velocity-proportional stopping extrapolates to zero stopping at larger values of velocity.

I. INTRODUCTION

Stopping powers in general are governed by various contributions from electron scattering, ionization and excitation of atoms of the target substance, and nuclear recoils in the target substance, as well as excitation and ionization of the moving ion. These contributions are dominant or negligible depending upon the velocity of the ion. At lowest velocities, nuclear recoils become an important factor in the stopping power. At somewhat higher velocities, ionization and excitation of both target atoms and moving ions as well as electron scattering dominate, and nuclear-recoil effects become a small correction factor in the stopping power. This second velocity region has come to be known as the region of velocity-proportional stopping, where the stopping power is expected to have the form $k\sqrt{E}$. It was once thought to extend from v_0 to $v_0 Z_1^{2/3}$, where v_0 is the electron velocity in the first Bohr orbit and Z_1 is the atomic number of the moving particle. We know that dE/dx for Br and I ions[1] begins to fall below a straight-line relationship above a velocity of $\frac{1}{3} v_0 Z_1^{2/3}$. Theoretical discussions of velocity-proportional stopping have been given by various authors.[2–8] The theories of Lindhard, Scharff, and Schiøtt[8] and Firsov[7] do not agree as to the predicted magnitudes of the stopping powers but they do agree

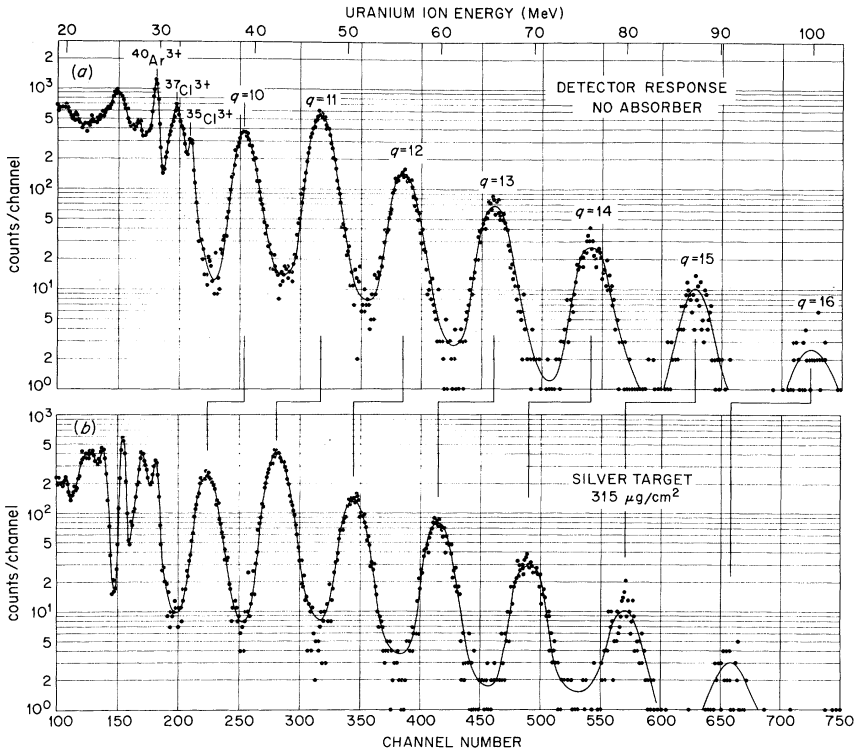

FIG. 1. Uranium-ion spectra observed with no absorber and with a 315-μg/cm^2 silver foil.

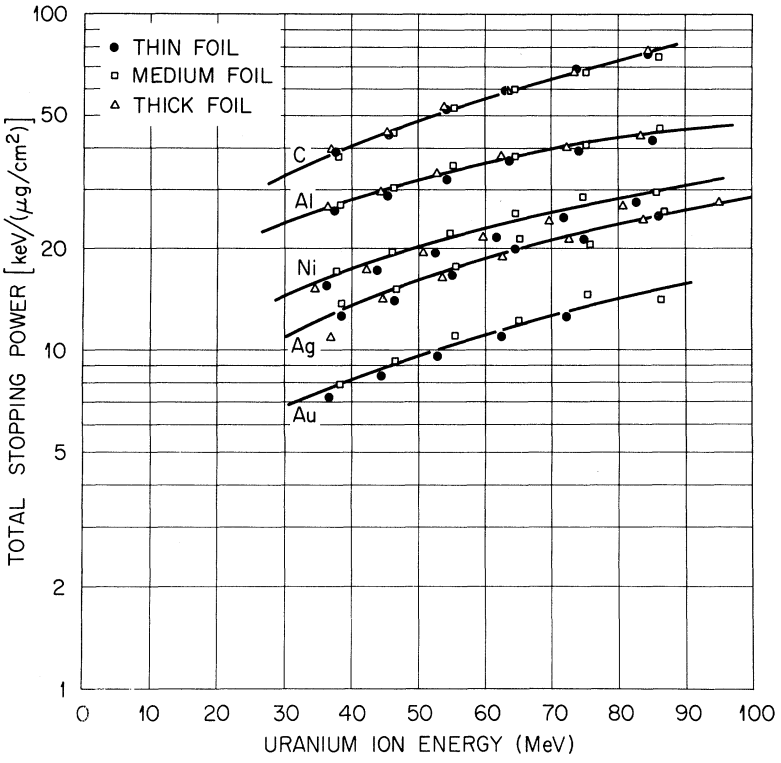

FIG. 2. Uranium-ion stopping powers vs ion energy.

upon one important point, viz., that if the small nuclear-stopping component is subtracted out, the residue, which is called electronic stopping, should have the form $k\sqrt{E}$. Extrapolation toward low velocity for this electronic-stopping-power component should pass through the origin. As will be seen, the form $k\sqrt{E}+b$ appears to be required to fit data for very heavy ions and it is clear that modifications, or interpretations, must be made to the existing theories. An energy-loss term due to charge exchange, as proposed by Teplova, Nikolaev, Dmitriev, and Fateeva, may be required to account for the differences between theory and experiment.[9]

II. EXPERIMENTAL RESULTS

Multicomponent beams of ^{238}U ions were obtained

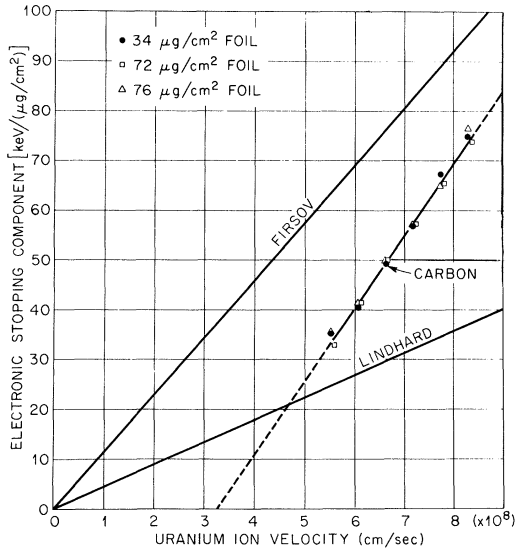

FIG. 3. Electronic component of uranium stopping power for carbon vs ion velocity.

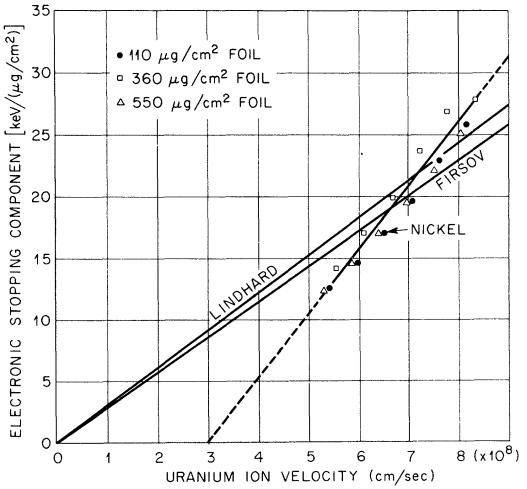

FIG. 4. Electronic component of uranium stopping power for nickel vs ion velocity.

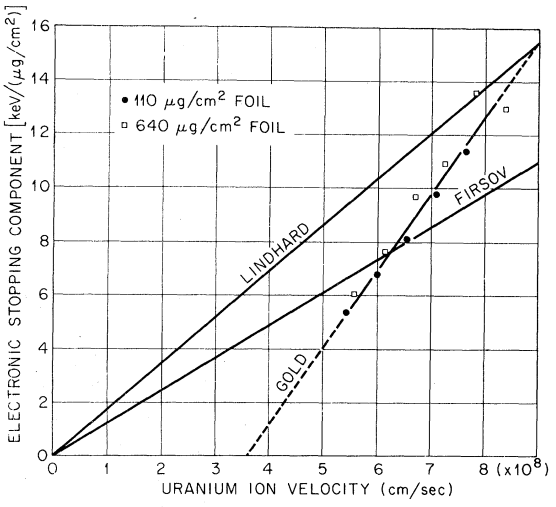

FIG. 5. Electronic component of uranium stopping power for gold vs ion velocity.

from the Oak Ridge Tandem accelerator; the accelerator technique has been described in an earlier paper.[10] Negative molecular ions containing uranium and chlorine were obtained from the ion-source charge-exchange canal, consisting of an oven partially filled with UCl_4. The terminal stripper of the accelerator produced positive ions of uranium, chlorine, and argon (the stripper gas). The series of uranium beams obtained were in the energy range 30–100 MeV and the 100-MeV component was charge-state 16. The two spectra shown in Fig. 1 illustrate the method of measurement. The widths of the peaks in the upper curve are almost entirely caused by the detector, since the energy resolution of the beam slices from the accelerator analyzer magnet corresponds to much less than 0.1-MeV full width at half-maximum.

Thicknesses of the foils used were measured by the α-particle energy-loss method. A thin α-particle source of ^{244}Cm was used with a Si surface-barrier detector to determine pulse-height spectra with and without each foil.[11] The over-all energy resolution of the source-detector-electronics system corresponded to 24 keV. Absorbers were sufficiently thick to give energy-loss accuracy within ±3%. Uncertainties in the α-particle stopping-power values gave an over-all uncertainty of ±5% or less for the foil-thickness determinations.

The results of the stopping-power measurements are shown in Fig. 2. Foil thicknesses were for carbon: 34, 72, and 76 $\mu g/cm^2$; for aluminum: 51, 112, and 186 $\mu g/cm^2$; for nickel: 110, 360, and 550 $\mu g/cm^2$; for silver: 58, 115, and 315 $\mu g/cm^2$; and for gold: 110 and 640 $\mu g/cm^2$. The over-all experimental uncertainty in the stopping powers is believed to be ±10%.

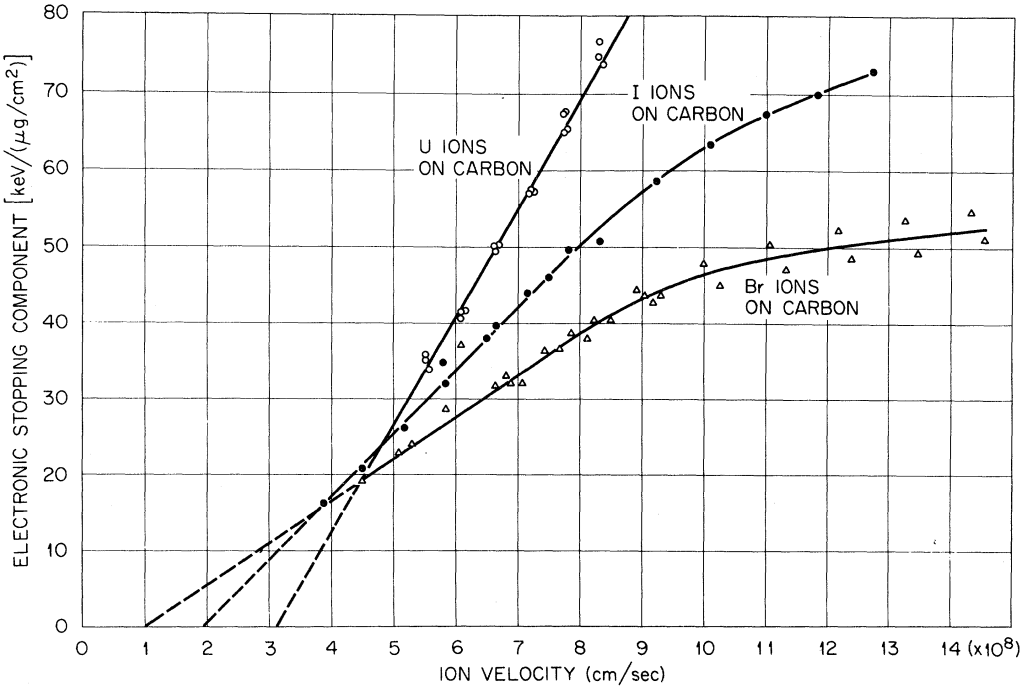

FIG. 6. Electronic component of U, I, and Br stopping power for carbon vs ion velocity.

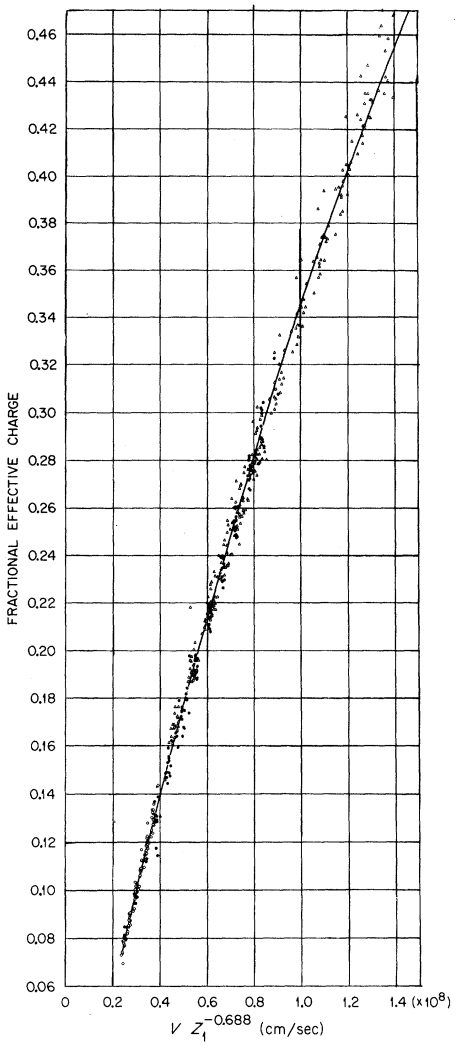

FIG. 7. Least-squares fit to U, I, and Br electronic stopping powers.

III. DISCUSSION

The data shown in Fig. 2 have been modified by subtracting a nuclear-stopping-power component. The nuclear stopping power used was an approximate expression given by Lindhard, Nielsen, and Scharff[12]:

$$\left(\frac{d\epsilon}{d\rho}\right)_n = \frac{1}{2\epsilon} \ln 1.294\epsilon, \quad \epsilon \geq 10 . \tag{1}$$

The results, called electronic stopping component, are illustrated in Figs. 3–5; similar curves for Al and Ag fall into the same general trend. All the data appear to fit straight lines when plotted against velocity, but in each case extrapolation downward does not produce an intercept at the origin as predicted by the theories of Lindhard, Scharff, and Schiøtt[8] or Firsov.[7] The nuclear-stopping component subtracted from the data ranged from 9 to 2.5% for carbon, 20 to 6% for Ni, and 26 to 8% for Au. Underestimation of the nuclear stopping would, if corrected, only serve to move the intercept to still higher velocity. Removal of the nuclear-stopping correction altogether would not bring the curves to an intercept at the origin.

Oak Ridge data for Br and I ions[1] have been corrected for nuclear stopping and plotted along with the data for U ions; an example for the case of carbon targets is shown in Fig. 6. For lighter ions the extrapolated intercepts fall nearer to the origin. The strictly linear portions of the curves appear to be limited to a rather narrow range of velocities between v_0 and $\frac{1}{3}Z_1^{2/3}v_0$. An important result was reported by Eriksson, Davies, and Jespersgaard for Xe ions moving in W crystalline channels.[13] Their data indicated that the stopping power was linear with velocity for all energies in the range 25 keV–1.5 MeV and that the line fitted to the data passed through the origin. For the case of crystal channels the stopping power is in general much smaller than that for amorphous substances, and nuclear stopping power would be expected to be quite negligible above 100 keV. It would appear that in amorphous substances where smaller ion-atom impact parameters can occur, the conditions for electronic stopping as described by Lindhard, Scharff, and Schiøtt are not sufficiently well met, or that other contributions to the stopping power must be taken into account.

IV. SEMIEMPIRICAL METHODS

In order to obtain a classification of stopping powers for purposes of interpolations with respect to energy and ion species, a description of stopping in terms of effective charge has been proposed.[14–19] The procedure is to relate the electronic stopping of a given heavy ion to that of the proton at the same velocity through the use of a parameter γ:

$$\left(\frac{dE}{dx}\right)_{Z,A,E} \Big/ \left(\frac{dE}{dx}\right)_{p,E/A} = \frac{\gamma^2 Z^2}{\gamma_p^2} , \tag{2}$$

where

$$Z_{eff} = \gamma Z \tag{3}$$

and Z_{eff} is the effective charge for stopping. These methods have been used to classify the data taken in Oak Ridge for Br, I, and U stopping powers. Over most of the energy range of interest here $\gamma_p = 1$. At the lower energies an empirical function due to Booth and Grant is used[20]:

$$\gamma_p^2 = (1 - e^{-150E_p}) \exp(-0.835\, e^{-14.5E_p}) , \tag{4}$$

where E_p is proton energy in MeV. Values of proton stopping power were taken from the tabulations of Northcliffe and Schilling.[14] More than 500 data

points were used to obtain a least-squares fit to the function shown as a solid line in Fig. 7. Although the individual points cannot be identified at journal figure size, the conclusions are the same for each of the three ions. The analytic function which was derived is

$$\gamma = 1 - 1.034 \exp[-(v/v_0)Z^{-0.688}] , \quad (5)$$

where $v_0 = 2.19 \times 10^8$ cm/sec and v is ion velocity in cm/sec. If either number (1.034 or 0.688) is varied by as much as 0.002, then no value of the other number will produce an equally good fit to the data. The data for U, I, and Br, treated separately, produced the same numbers as given in Eq. (5). The function derived in Eq. (5) can be used to obtain estimates of electronic stopping power for heavy ions with $Z \geq 35$. To these values a small contribution due to nuclear stopping should be added as derived from Eq. (1) to obtain the total stopping power.

It is interesting to observe that the values of effective charge for stopping happen to agree so closely with the average ionic charge emerging from gas targets for Br and I ions.[21,22] From 20 to 110 MeV, Br-ion stopping-power measurements and gas-equilibrium charge-distribution measurements lead to the conclusion that Z_{eff} for stopping is the same as the measured average ionic charge within the present limits of uncertainty (viz., ±10% for dE/dx and ±1 charge-state variation for different gases). For I ions from 20–100 MeV, the agreement falls somewhat outside this range of uncertainty at the upper end of the velocity range (Z_{eff} is ~13% lower than typical values of $\langle q \rangle$). For the case of solid targets the emerging charge-state distributions are shifted to much higher charge due to the very short time between collisions.

At low energies, when stopping powers of different ions are compared, periodic oscillations with Z_1 are observed.[23,24] The effect is known to be larger for particles moving in crystalline channels than for particles moving in amorphous solids.[13] From the tables and curves given by Northcliffe[14] we conclude that above 0.04 MeV/amu oscillations of stopping powers with Z_1 (of the ion) and Z_2 (of the medium) are small and more difficult to measure. The number of ion types and the number of target elements being discussed here are too small to give a clear indication of such effects. At any rate, the stopping-power curves reported here do not extrapolate to the origin as expected, regardless of the scale factor as influenced by Z_1 or Z_2.

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[1]C. D. Moak and M. D. Brown, Phys. Rev. 149, 244 (1966).

[2]N. Bohr, Phys. Rev. 58, 654 (1940).

[3]N. Bohr, Phys. Rev. 59, 270 (1941).

[4]W. E. Lamb, Jr., Phys. Rev. 58, 696 (1940).

[5]J. Knipp and E. Teller, Phys. Rev. 59, 659 (1941).

[6]J. H. M. Brunings, J. Knipp, and E. Teller, Phys. Rev. 60, 657 (1941).

[7]O. B. Firsov, Zh. Eksperim. i Teor. Fiz. 36, 1517 (1959) [Sov. Phys. JETP 9, 1076 (1959)].

[8]J. Lindhard, M. Scharff, and H. E. Schiøtt, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 33, 14 (1963).

[9]Teplova, Nikolaev, Dmitriev, and Fateeva, Zh. Eksperim. i Teor. Fiz. 42, 44 (1962) [Sov. Phys. JETP 15, 31 (1962)].

[10]C. D. Moak, H. I. Neiler, H. W. Schmitt, F. J. Walter, and G. F. Wells, Rev. Sci. Instr. 34, 853 (1963).

[11]The α-particle source was kindly supplied by R. J. Silva of the Chemistry Division of ORNL.

[12]J. Lindhard, V. Nielsen, and M. Scharff, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 36, 10 (1968).

[13]L. Eriksson, J. A. Davies, and P. Jespersgaard, Phys. Rev. 161, 219 (1967).

[14]L. C. Northcliffe and R. F. Schilling, Nucl. Data Tables A7, 322 (1970).

[15]H. L. Heckman, B. L. Perkins, W. G. Simon, F. M. Smith, and W. H. Barkas, Phys. Rev. 117, 544 (1960).

[16]P. G. Roll and F. E. Steigert, Phys. Rev. 120, 470 (1960).

[17]S. D. Bloom and G. D. Sauter, Phys. Rev. Letters 26, 607 (1971).

[18]T. E. Pierce and M. Blann, Phys. Rev. 173, 390 (1968).

[19]R. Kalish, L. Grodzins, F. Chmara, and P. H. Rose, Phys. Rev. 183, 431 (1969).

[20]W. Booth and I. S. Grant, Nucl. Phys. 63, 481 (1965).

[21]C. D. Moak, H. O. Lutz, L. B. Bridwell, L. C. Northcliffe, and S. Datz, Phys. Rev. 176, 427 (1968).

[22]S. Datz, C. D. Moak, H. O. Lutz, L. C. Northcliffe, and L. B. Bridwell, Atomic Data 2, 273 (1971).

[23]J. H. Ormrod, J. R. Macdonald, and H. E. Duckworth, Can. J. Phys. 43, 275 (1965).

[24]B. Fastrup, P. Hvelplund, and C. A. Sautter, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 35, 10 (1966).