Some Heavy-Ion Stopping Powers*

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Multicomponent Br and I beams from the Oak Ridge Tandem Accelerator have been used to measure the stopping powers of Be, C, Al, Ni, Ag, and Au over the energy range 10 to 100 MeV.

MEASUREMENTS of ranges and stopping powers of very heavy ions have been accomplished in the past through the use of fission particles. In one experiment of this type radiochemical analyses were used to measure depth of penetration in stacked foils for various fission fragments.[1] Ionization versus fission-fragment energy in gases has been studied in order to derive stopping power information.[2] Collections of much of the information on the passage of heavy ions through matter have been given by Whaling[3] and by Northcliffe.[4] Recent measurements include stopping power determinations for fission fragments in light gases.[5] Until recently, very heavy ions of known mass and accurately known energies covering the range from 10 to 100 MeV have not been available. The multicomponent heavy ion beams available from the Oak Ridge Tandem Accelerator have been described earlier[6] and these beams have been used for measurements of the stopping powers of several elements for I ions.[7] The results reported here have been broadened to include more elements and to include stopping powers for Br ions.

As described earlier,[7] the experimental procedure was to measure the pulse heights in a solid-state detector for the components of the beam and then to measure the pulse-height shifts caused by thin foils of various elements placed in the beam before the detector. These pulse-height shifts, converted to energy shifts, were used together with the thicknesses of the foils, to estimate values of the stopping power dE/dx. Foil thicknesses were chosen to produce energy losses of less than 10 MeV. Thicknesses were measured by α-particle dE/dx measurements on the foils actually used in the experiments.[3,8] The foils were prepared by evaporation techniques and none of these showed any evidence of crystal-channel effects[9] and were judged to be polycrystalline.

The stopping powers derived from the data are shown in Figs. 1 and 2. Errors of measurement in the α-particle thickness measurements, uncertainties in the values assumed for α-particle stopping powers, combined with errors of measurement for the I or Br ions, gave an estimated probable error of $\pm 10\%$ for the stopping powers shown. Uncertainties in the relative values between the various curves are believed to be $\pm 5\%$. Data were taken separately for ^{79}Br and ^{81}Br; no differences in stopping power were observed for the two isotopes,

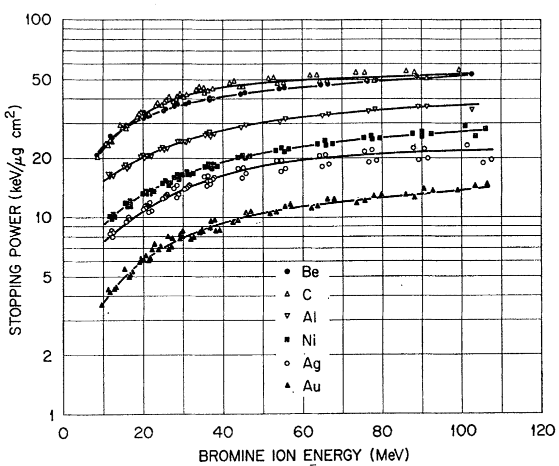

FIG. 1. Stopping power of several elements for bromine ions.

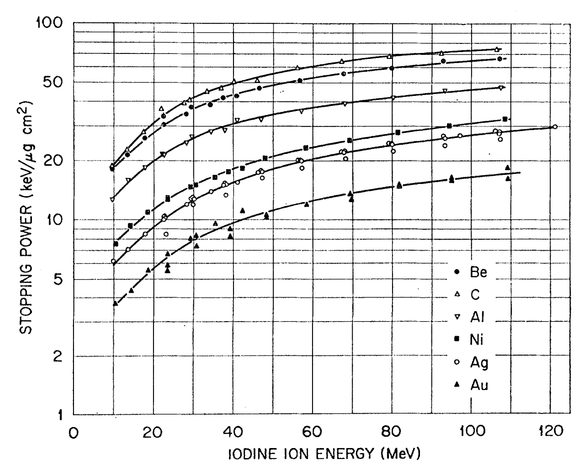

FIG. 2. Stopping power of several elements for iodine ions.

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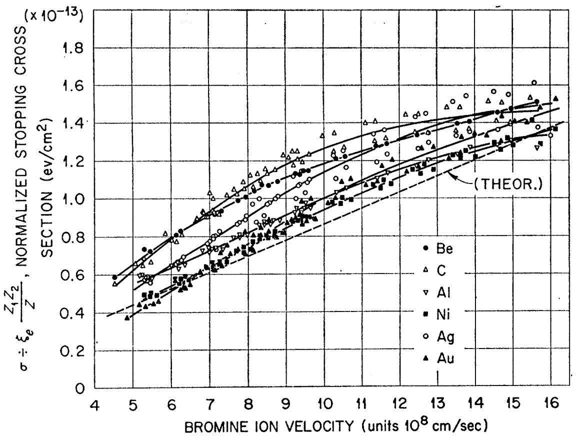

FIG. 3. Normalized stopping cross sections for bromine ions.

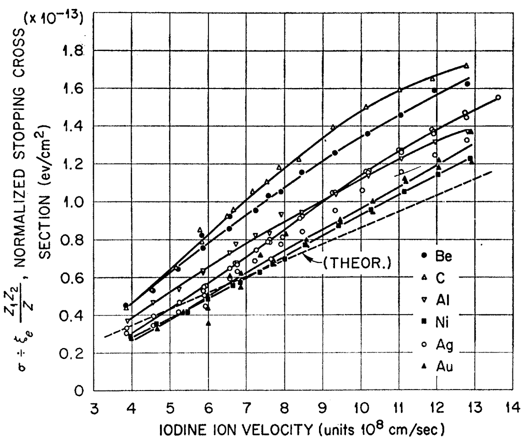

FIG. 4. Normalized stopping cross sections for iodine ions.

within the limits of experimental error. No effort has been made to take into account the effect of oxidation of the foils which were used; however, in some cases, different foil thicknesses did not indicate this effect to be important.

The rate at which charge-state equilibrium is reached in the foils is not known. A subsidiary experiment was performed wherein the energy of one particle group was kept fixed and the accelerator magnet field was changed so as to vary the charge of that group through a range of five units. The stopping power measured for that group was found to be independent of incident charge. We conclude that charge-state equilibrium occurs sufficiently rapidly that no effect is produced upon the measured stopping powers; this would mean that in most foils used, equilibrium occurs within the first 50 μg/cm^2.

For the particle energies which were used in these experiments, the equilibrium charge of the ion is strongly dependent upon its velocity in the medium. This accounts for the fact that the stopping power falls off toward lower energy. According to Lindhard *et al.*[10] this should be the region of velocity-proportional stopping and the stopping cross section should be

$$S_e = \xi_e 8\pi e^2 a_0 \frac{Z_1 Z_2}{Z} \frac{v}{v_0}, \quad v < v_1 = v_0 Z_1^{2/3}, \qquad (1)$$

where Z_1 and Z_2 are atomic numbers of particle and medium, respectively, ξ_e is a constant approximately equal to $Z_1^{1/6}$, $a_0 = \hbar/me^2$, $v_0 = e^2/\hbar$, and $Z^{2/3} = Z_1^{2/3} + Z_2^{2/3}$. For purposes of comparison, our data have been converted to atomic stopping cross sections and then divided by $\xi_e Z_1 Z_2/Z$ and plotted as functions of velocity. The result is shown in Figs. 3 and 4; these normalized stopping cross section curves show the predicted linear trend with velocity. The higher velocity Br curves show a tendency to level off at the upper end of the velocity scale as expected and it is assumed that at still higher velocity the cross sections would begin to decrease with energy.

The parameter ξ_e in Eq. (1) is expected to vary somewhat, and Ormrod, MacDonald, and Duckworth[11] have found a cyclic variation of ξ_e with Z_1 for the case of low energy ions with $1 \leq Z_1 \leq 19$. In the cases studied, values of ξ_e were reported to vary through a factor of 2 about a mean value of $Z_1^{1/6}$. For the data reported here a 28% increase in the value of ξ_e above the nominal value $Z_1^{1/6}$ would give a fairly good fit to the estimated stopping powers.

The shape of the stopping power curves reported here suggests that the ranges of fission fragments will in most cases be of the form $R = Av - \Delta$. In all data reported here, the stopping powers fit the relationship

$$dE/dx = \alpha v^k, \qquad (2)$$

where k is very nearly unity but somewhat less than unity for Br ions of highest velocity. Equation (2) reduces to

$$dv/dx = \beta v^{(k-1)}, \qquad (3)$$

and thus $(k-1)$ does not reach positive values for the data reported here. Leachman and Schmitt have shown that if $(k-1)$ is positive, then absorbers may be used in fission studies to achieve isobaric velocity bunching.[12] Their results seemed to indicate some isobaric velocity bunching for Al and Ni but not for Au. The results reported here would seem to indicate that the condition for isobaric velocity bunching $(k-1) > 0$ is not met for Al, Ni, or Au. It may be that variations in range straggling with particle mass could account for the reported results.

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