SLOWING DOWN OF 0.5–30 keV PROTONS IN SOME MATERIALS

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Experimental results are given for the energy lost by 0.5–30 keV protons in C, Ti, Al, Cu, Ni, Fe, Ge, Si, Sb, and Bi. It is shown that the experimental data are in qualitative agreement with the theory.

EXPERIMENTAL investigations of the slowing down of low-energy protons in matter are very difficult. It is sufficient to mention that at present the stopping powers of protons with energies $E < 3–5$ keV are known only for silver.[1,2]

The present paper describes a study of energy losses of protons with E = 0.5–30 keV in carbon, titanium, aluminum, copper, nickel, iron, germanium, silicon, antimony, and bismuth.

APPARATUS

The apparatus used is shown schematically in Fig. 1. An ion beam, emerging from a source 1, was focused by an electrostatic lens and split in accordance with ion masses in the magnetic field of a separator 2. After the separator, the protons struck a foil of the investigated material 3. The transmitted ions were analyzed according to their energies in an electrostatic analyzer 4 and recorded with an open electron multiplier 6.

The analyzer plates were of special shape[3] and this made it possible to focus an ion beam so that its angle of divergence was ±4°. The resolving power of the analyzer was $E/\Delta E = 20$. The electron multiplier was made up of 20–30 dynodes taken from photomultipliers type FÉU-15 or FÉU-16. The amplification of the electron multiplier was $10^4–10^6$. The signal from the multiplier was amplified by a dc amplifier and recorded automatically.

The investigated materials were in the form of free foils, 100–500 Å thick. These foils were prepared, in vacuum, by thermal evaporation of a given material on to a glass substrate coated with a thin layer of a solution of potash soap in alcohol.[4] After the evaporation of the material, the soap was dissolved in distilled water and each foil was placed on a fine-mesh copper or nickel grid (250–750 mesh number and a permeability of 60–70%). The foil thickness was determined from the absorption of light of wavelength 5250 ± 50 Å.

The intensity of light of wavelength λ, transmitted by a layer whose thickness is d, is given by the formula

$$I = I_0 \exp\left(-\frac{4\pi}{\lambda}\alpha d\right), \qquad (1)$$

where I_0 is the intensity of the incident light and α is the absorption coefficient. We determined α by the simultaneous evaporation of a film of each material on a large-area metal substrate and on glass. To ensure that the influence of the substrate on the properties of the foil was the same, the metal and glass substrates were covered with a solution of potash soap in alcohol.

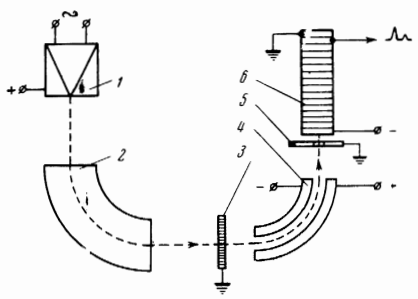

FIG. 1. Schematic diagram of apparatus: 1) ion source; 2) magnetic separator; 3) foil; 4) electrostatic analyzer; 5) iris; 6) electron multiplier.

FIG. 2. Edge-on photographs of Bi foil: a) 200 Å thick; b) 500 Å thick.

By weighing the metal substrate before and after evaporation and using the tabulated values for the density of the evaporated material, we determined the foil thickness d. The absorption of light in the film deposited on glass was used to determine the ratio I/I_0. The values of α obtained in this way are given in Table I.

The value of α for C was determined by Myers and Montet[5] and found to be 1.15. The values of α obtained in the present investigation and those reported by Myers and Montet[5] differed by about 7%.

Investigation of C, Ag, and Bi foils by electron diffraction showed that they were polycrystalline and that the crystallites were very small. The densities of the foils were lower than the tabulated values. Figure 2 shows photographs of the ends of bismuth foils 200 Å (a) and 500 Å (b) thick. It is clear from Fig. 2 that the geometrical thickness of the foils was approximately

material	α	material	α
C	1.23±0.02	Fe	1.93±0.08
Ti	4.1±0.4	Ge	3.9±0.1
Al	4.1±0.36	Si	0.54±0.16
Cu	1.6±0.2	Sb	3.1±0.1
Ni	3.2±0.1	Bi	3.6±0.2

twice as large as the thickness determined by the method just described.

Details of the structure of thin films, prepared by evaporation in vacuum, depend on the substrate on which they are evaporated. To check the influence of the substrate on the stopping power of foils, we measured the energy losses of protons in aluminum and nickel foils prepared by a method different from that described at the beginning of this section. In the case of Al, we used a nitrocellulose substrate, which was dissolved in acetone. In the case of Ni, we used an Al substrate, which was dissolved in an alkali, or a copper substrate, which was dissolved in a solution recommended in[6]. In every case, the measured specific energy losses were found to be independent of the nature of the substrate used in the preparation of a foil.

RESULTS OF MEASUREMENTS

In measurements of the energy losses, we used 4–8 foils of various thicknesses of any one given material. The value of the specific energy losses of protons in a foil were defined by

$$-dE / dx = (E_2 - E_1) / d, \qquad (2)$$

where E_1 is the energy of the proton incident on the foil, E_2 is the energy of the proton after passing through the foil, and d is the foil thickness. These specific energy losses were related to the velocity of the proton, corresponding to the average energy of the proton in the foil, i.e., to the velocity

$$v = \sqrt{(E_1 + E_2) / 4M}, \qquad (3)$$

where M is the proton mass. The dependences of the specific energy losses on the velocity of protons in various materials are given in Figs. 3–9. The rms experimental error did not exceed 10%.

1. Carbon (Fig. 3). It is evident from the figure that the specific energy losses are approximately proportional to the proton velocity in the range $(0.13–1.7) \times 10^8$ cm/sec (0.09–15 keV). The results taken from[7], which are included in Fig. 3, differ slightly from our results.

2. Titanium (Fig. 4). Our results differ from those given in[1] by less than 10% ($0.7 \times 10^8 < v < 1.7 \times 10^8$ cm/sec). The specific energy losses are approximately proportional to the proton velocity in the range $0.6 \times 10^8 < v < 1.7 \times 10^8$ cm/sec. This proportionality is not observed at lower and higher velocities.

3. Aluminum (Fig. 5). The largest amount of published experimental data is available for Al.[9,12,13] However, it is evident from Fig. 5 that the published results are contradictory and agree poorly with our results.

Curve 2 in Fig. 5 is based on measurements of the proton range in Al reported in[12]. Multiple scattering of protons in matter, which becomes important at low energies, is the cause of the basic disagreement between the results reported in[12] and by other workers. The specific energy losses are proportional to the proton velocity in the range $0.35 \times 10^8 < v < 1.4 \times 10^8$ cm/sec.

4. Copper (Fig. 6). The best agreement between the published results[8,9] and our data is observed for copper. It must be mentioned that Zarutskiĭ[8] found a deviation of the specific losses from the linear dependence on the velocity at $v < 0.8 \times 10^8$ cm/sec. We did not observe such a deviation.

5. Nickel (Fig. 7). As in the case of Al, there is a large difference between the results reported for Ni in[10,11] and those obtained by us. The dependence of the specific energy losses on the velocity is nonlinear at $v < 0.8 \times 10^8$ cm/sec and $v > 1.7 \times 10^8$ cm/sec.

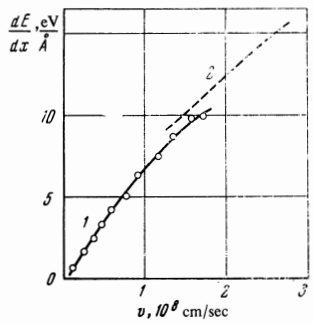

FIG. 3. Specific energy losses in C: 1) our results; 2) [7].

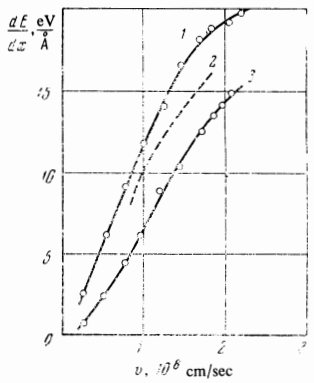

FIG. 4. Specific energy losses in Ti and Fe: 1) Ti, our results; 2) Ti, [1]; 3) Fe, our results.

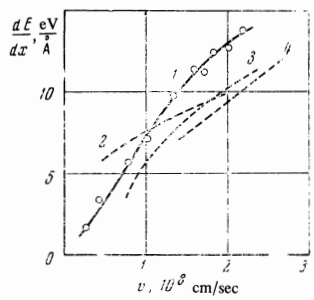

FIG. 5. Specific energy losses in Al: 1) our results; 2) [12]; 3) [9]; 4) [13].

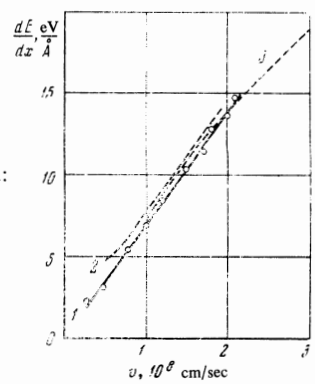

FIG. 6. Specific energy losses Cu: 1) our results; 2) [8]; 3) [9].

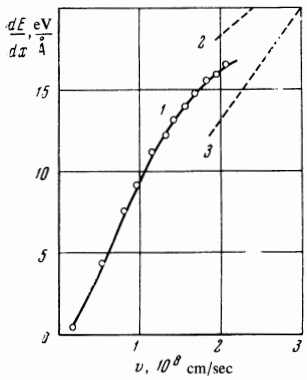

FIG. 7. Specific energy losses in Ni: 1) our results; 2) [10]; 3) [11].

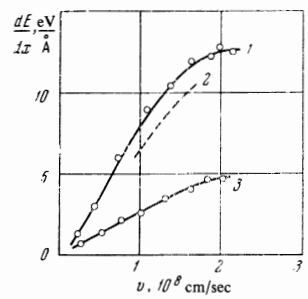

FIG. 8. Specific energy losses in Ge and Si: 1) Ge, our results; 2) Ge, [1]; 3) Si, our results.

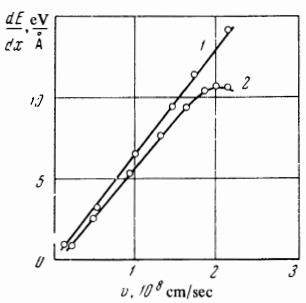

FIG. 9. Specific energy losses in Bi and Sb: 1) Bi, our results; 2) Sb, our results.

6. Germanium (Fig. 8). Our results differ by 10–15% (in the range $0.9 \times 10^8 < v < 1.7 \times 10^8$ cm/sec) from those reported in[1]. The specific energy losses are proportional to the proton velocity in the range $0.8 \times 10^8 < v < 1.3 \times 10^8$ cm/sec.

7. Iron (Fig. 4), silicon (Fig. 8), antimony (Fig. 9), and bismuth (Fig. 9). The energy losses of protons in these materials, in the velocity range 0.3×10^8–2.2×10^8 cm/sec, had not been determined before. The dependences of the specific energy losses on the proton velocity for these materials are similar to those for the other substances investigated.

In the proton energy range investigated in the present study, the energy losses are mainly due to the collisions of a moving particle with electrons in the foil. The energy losses in collisions with target atoms are very small for protons whose energies exceed 100 eV and, therefore, these losses can be neglected.[14]

The slowing down of particles moving in a metal was investigated theoretically in[15,16] and it was shown that if the velocity of the incident particle is less than the Fermi velocity of electrons in the metal, the energy losses should be proportional to the particle velocity.

An analysis of the interaction between a low-energy proton and the Thomas-Fermi potential also yields a linear dependence of the energy losses on the velocity.[14] However, calculations reported in[2] show that this dependence applies only at velocities $v \ll v_F$ and that at $v \approx v_F$ the dependence is no longer obeyed. In this sense, the results given in[2] contradict those obtained by Lindhard and Winther[16], who found that the linearity was retained right up to $v \approx v_F$.

The values of the specific losses calculated using the results given in[2,14,15,16] are usually several times smaller than the experimental values.

The experimental data indicate that the specific energy losses in the investigated targets are proportional to the proton velocity in the range $0.8 \times 10^8 < v < 1.7 \times 10^8$ cm/sec. Some of the materials (Ti, Ni, Ge, Fe, Ag) exhibit a departure from the linearity at $v < 0.8 \times 10^8$ cm/sec and the losses are always smaller than those which would be obtained in the case of a linear dependence of the losses on the proton velocity. A deviation of the energy losses from a linear to a superlinear dependence, reported in[8], was not found in our investigation. Zarutskiĭ[8] explained the superlinear dependence by the fact that at low velocities the energy losses in collisions with whole atoms begin to have an effect. However, calculations showed that the energy losses in collisions with whole atoms were approximately 20 times smaller than the measured losses (at $v > 0.3 \times 10^8$ cm/sec).

Thus, we may conclude that the experimentally found energy losses of protons in some materials (C, Al, Cu, Si, Sb, Bi) are in qualitative agreement with the theoretical predictions given in[14–16] while losses in other materials (Ti, Ni, Ge, Fe, Ag) are in agreement with the calculations given in[2]. The theoretical values of the energy losses are 2–3 times lower than the experimental values.

In conclusion, the authors express their deep gratitude to E. P. Senchenkov for electron-microscopic studies.

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131