Stopping Cross Sections of Metals for Protons of Energies from 400 to 1000 kev*

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The stopping cross sections of manganese, copper, germanium, selenium, silver, tin, antimony, gold, lead, and bismuth are reported for protons in the energy range 400 to 1000 kev. The cross sections are roughly proportional to the square root of the atomic number of the stopping element and inversely proportional to the velocity of the incident protons. There is some evidence that the stopping cross section increases more rapidly than $Z^{\frac{1}{2}}$ as the various p shells are filled.

I. INTRODUCTION

STOPPING power has been the subject of interest and extensive investigation since the earliest days of nuclear physics.[1] From almost the very beginning the range of an energetic charged particle has been used as a measure of its energy. These range-energy relations were first experimentally investigated by observing alpha particles from natural radioactive sources. With the development of the particle accelerators it became possible to obtain protons and other charged particles with well defined energy. The development of techniques for obtaining thin foils permitted the direct observations of the rate of energy loss as a function of energy rather than its inference from range measurements.

Theoretical aspects of the problem have been investigated by a number of physicists. Of particular importance are the early treatments by Bohr[2] using a classical approach and by Bethe[3] and Bloch[4] using the quantum mechanical approach. The expressions obtained have been reasonably successful in predicting the experimental results for higher energies. However, one of the basic assumptions involved in these theories is that the velocity of the particle is greater than the orbital velocity of the atomic electrons of the stopping material. As a consequence, the results for low particle velocities have not been entirely satisfactory. Several attempts have been made to correct this deficiency,[5,6] but none has proved completely adequate. Therefore, experimental data must be relied upon in this velocity range.

Of more immediate concern here are the expressions derived by Bohr[7] and more recently by Lindhard and Scharff[8] using a statistical approach based on the Thomas-Fermi model of the atom. While these forms are not expected to give accurate results, they do predict a relationship between the stopping power, the atomic number, and the velocity of the particles. The testing of these relations for various energies and stopping media is desirable. In this paper, data on the stopping cross sections of the elements manganese, copper, germanium, selenium, silver, tin, antimony, gold, lead, and bismuth are reported and compared with these theoretical predictions.

II. EXPERIMENTAL TECHNIQUE

The experiments were carried out using protons accelerated by a Van de Graaff generator. The acceleration voltage was stabilized by detecting an unbalance in proton current intercepted by defining slits and automatically altering the corona drain to bring the beam back to a balanced position. The energy of the protons was determined from current in the coils of the analyzing magnet which was calibrated by the use of the lithium and fluorine (p,γ) resonances.[9]

The method used was a modification of the one suggested and developed by Madsen and Venkateswarlu.[10] In this technique, an excitation spectrum for a proton reaction with some target material is obtained first without, and then with a foil of a stopping medium inserted in the proton beam. The energy loss suffered by the protons in the stopping material is indicated by the apparent shift in the resonance peaks of the reaction spectrum. This technique suffers a serious limitation in the fact that most materials do not lend themselves to the formation of foils which are sufficiently thin, and yet strong enough to be suitable.

To overcome this difficulty a technique was developed[11] in which the stopping material was evaporated directly onto the target material. (This modification was proposed and used independently by Madsen[12]

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although he confined its application to those materials which would also produce foils.) This arrangement quite naturally gives rise to the name "sandwich target" since the target material is sandwiched between the target backing and the stopping material. For this work, LiF was used exclusively as the target material and tantalum was generally used for the target backing. The resonance energy levels for the (p,γ) reactions are accurately known[9] for both lithium and fluorine.

One of the complications introduced by the use of sandwich targets is the problem of determining accurately the thickness of the target material (LiF). The displacement of a resonance level is greater than that due to the stopping material by an amount equal to one half the energy thickness of this LiF layer. Since the target thicknesses used were in the neighborhood of five kev, it became necessary to take this into account. By using a calibration target evaporated at the same time as the sandwich target, the effect of the target thickness cancels out on the assumption that the LiF is the same thickness on both targets.

The necessity of making a simultaneous calibration run each time a sandwich target was run required a switching apparatus in the vacuum system which permitted inserting either a calibration target or a sandwich target in the proton beam as desired. The target assembly formed part of the Faraday cage which was connected to an integrator to measure the charge incident on the target. The gamma rays from the target were detected by a cylindrical 1.5×1.5 inch NaI crystal and a 5819 photomultiplier tube.

III. TARGETS

The general method of preparing targets was to evaporate lithium fluoride on the target blank, weigh the blank, evaporate the stopping material onto the lithium fluoride, and weigh the target again. The blanks were circular with a diameter of 0.5 inch. Tantalum was the usual material, although a few were copper or silver. The weighings were done on a microbalance which gave weights consistently reproducible

TABLE I. Summary of results on stopping power for protons.

Proton energy (kev)	Stopping power (kev/mg/cm²) Mn	Cu	Ge	Se	Ag	Sn	Sb	Au	Pb	Bi
400	218	179	177	168	150	142	146	96	100	104
450	206	172	168	160	142	135	138	92	95	99
500	196	165	159	154	135	128	132	88	90	94
550	186	158	153	148	128	122	125	84	86	90
600	177	152	147	143	121	116	119	80	82	86
650	169	147	142	138	116	111	113	78	79	82
700	162	142	138	134	111	107	108	75	75	79
750	156	137	133	130	107	103	104	73	73	75
800	151	133	130	126	103	100	101	71	70	73
850	147	128	126	122	101	97	98	69	68	70
900	143	125	123	120	98	94	96	67	67	69
950	140	122	119	117	96	91	93	65	65	67
1000	136	119	116	115	94	89	91	64	64	66

TABLE II. The atomic stopping cross section (ev cm²×10⁻¹⁵) of elements for protons as a function of proton energy.

Proton energy (kev)	Element Mn	Cu	Ge	Se	Ag	Sn	Sb	Au	Pb	Bi
400	19.9	18.9	21.3	22.0	26.9	28.0	29.5	31.4	34.4	36.1
450	18.8	18.2	20.2	21.0	25.4	26.6	27.9	30.1	32.7	34.4
500	17.9	17.4	19.2	20.2	24.2	25.2	26.7	28.8	31.0	32.7
550	17.0	16.7	18.4	19.4	22.9	24.0	25.2	27.5	29.6	31.3
600	16.1	16.0	17.7	18.7	21.7	22.8	24.1	26.2	28.2	29.9
650	15.4	15.5	17.1	18.1	20.8	21.9	22.8	25.5	27.2	28.5
700	14.8	15.0	16.6	17.6	19.9	21.1	21.8	24.5	25.8	27.4
750	14.2	14.5	16.0	17.0	19.2	20.3	21.0	23.9	25.1	26.1
800	13.8	14.0	15.7	16.5	18.5	19.7	20.4	23.3	24.1	25.4
850	13.4	13.5	15.2	16.0	18.1	19.1	19.8	22.6	23.4	24.3
900	13.1	13.2	14.8	15.7	17.6	18.5	19.4	21.9	23.0	24.0
950	12.8	12.9	14.3	15.3	17.2	17.9	18.8	21.3	22.4	23.3
1000	12.4	12.6	14.0	15.1	16.8	17.5	18.4	21.0	22.0	23.0

to better than ten micrograms. With this sensitivity, it was necessary to deposit at least one milligram of stopping material to keep the weighing error under one percent.

The evaporations were carried out in a vacuum of 10^{-4} mm of mercury or better. The evaporating baskets were made of 0.020-in. tungsten wire wound in a conical shape with a diameter of 0.5 inch at the open end. The wire was coated with a paste of levigated alumina which was allowed to dry and then baked in a vacuum by passing a current through the coil. During evaporation the targets were mounted about six inches above the basket. The lithium fluoride was deposited on five target blanks at a time. The central blank of this cluster was used as the lithium fluoride calibration target for the other four which were subsequently made into "sandwich" targets. The stopping material was evaporated onto two of the blanks at a time. Comparison of the average thickness of the stopping material of the two targets gave an indication of the uniformity of the deposit. In most instances the two values agreed within two percent.

There are several reasons for believing that the thickness of the stopping material on a given target blank was sufficiently uniform so that thickness variations did not make a major error contribution. These thickness variations quite naturally fall into two categories: microscopic fluctuations covering an area smaller than that spanned by the proton beam and macroscopic ones extending over an area larger than that covered by the beam. Small fluctuations of the first type do not introduce serious errors in stopping cross section since the average energy loss corresponds closely to the average thickness. However, microscopic variations will produce a very noticeable effect in the straggling. Most of the data were not suitable for detailed straggling analysis, but rough calculations indicate that the non-uniformity never exceeded five percent and was less in a majority of cases.

Macroscopic fluctuations, on the other hand, can introduce serious errors. Macroscopic uniformity was carefully checked by running a few of the targets several times, making sure that the beam struck a different area of the target each time. The results of this in-

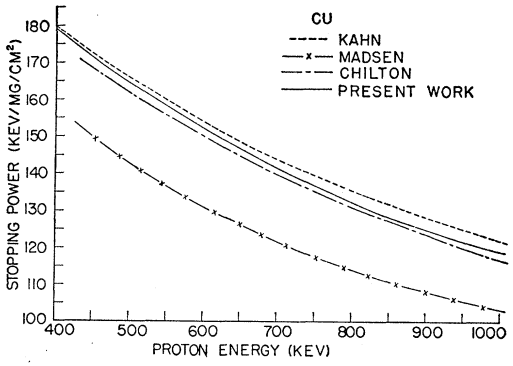

FIG. 1. The stopping power of copper for protons as a function of proton energy. Also plotted are the curves reported by Madsen (see reference 12), by Kahn (see reference 14), and by Chilton, Cooper, and Harris (see reference 13).

vestigation were consistent with the information obtained from the variation in average thickness previously referred to; namely, that the maximum thickness change from one side of the target to the other was about two percent. Since the targets were ordinarily positioned so that the beam struck the center of the target, the actual thickness should correspond closely to the average thickness. Further evidence of target uniformity comes from the internal consistency of the data from one stopping layer to another (for both foils and sandwich targets). Agreement was within five percent, except in the case of selenium.

In the study of copper and gold, foils were also used. They were made by evaporating the metal onto a microscope cover glass which was weighed before and after the evaporation. The foil was floated off the glass with distilled water and mounted on a frame which was then used in the same apparatus as has been described by Chilton, Cooper, and Harris.[13] Results from the foils agreed very well with those obtained from the sandwich targets.

The silver, tin, lead, and part of the gold used were obtained from the Fischer Scientific Company. The other materials were obtained from the Chemistry Department of The Ohio State University. All were of cp quality. As a further check, a semiquantitative spectrographic analysis was run on one target of each material after it had been bombarded. No significant amount of impurities was found in any of them. The analysis would not be expected to show carbon contamination.

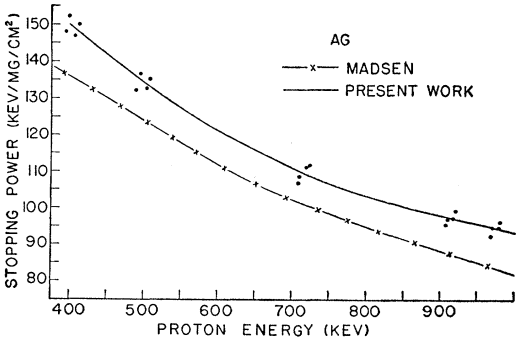

FIG. 2. The stopping power of silver for protons as a function of proton energy. Also plotted is the curve reported by Madsen (see reference 12).

[13] Chilton, Cooper, and Harris, Phys. Rev. **93**, 413 (1954).

IV. RESULTS

At least four separate targets were used for each of the stopping materials studied. The bombardment of each target was limited to about one microampere-hour to minimize the effect of carbon formation resulting from bombardment with the beam. Foils however, were run approximately twice this long as a rule. Each target run usually gave the stopping power at five different proton energies so the curve for each material was determined with a minimum of 18 to 20 points. Curves were drawn to make the best fit of the points, and the values appearing in Table I were read from these curves. The atomic stopping cross sections were computed from the data of Table I and are listed in Table II.

TABLE III. Target thicknesses in mg/cm².

Au	Sb	Sn	Mn	Cu	Ag	Pb	Bi	Se	Ge
1.16[a]	0.79	1.00	0.82	0.74	0.98	1.07	1.10	0.79	0.72
1.22[a]	1.07	0.78	0.80	0.72	0.74	1.04	1.40	1.34	0.70
0.84	1.08	0.99	0.75	0.86	0.93	1.74	1.10	1.28	0.81
0.85	0.79	0.83	0.78	0.89	0.77	1.78	1.43	0.81	0.81
1.23[a]				0.98[a]			0.88	0.88	
							0.84	0.92	
								0.75	

[a] Indicates foil.

The stopping power dE/dx determined from the displacement of a resonance level, was assigned to the average energy of protons in the stopping material. Chilton[13] has derived a correction to this average energy but in all cases the correction was so small that it could be neglected without increasing the probable error significantly.

The probable error for the curves is estimated to be about 2.5 percent, except in the case of selenium where it is about four percent. The energy loss suffered by the protons in the stopping material ranged from 70 kev to 150 kev in most cases and the peak positions could be read to better than one kev, so the error involved in the energy loss determinations was approximately one percent. The area of the targets was known to 0.25 percent. The weight of the stopping material ranged from 0.9 mg to 1.7 mg (see Table III) and the weight was accurate to about 0.01 mg which again gives an error of approximately one percent. The effect of other factors, such as carbon deposition during bombardment and non-uniformity of stopping layers, was checked several times but little if any contribution was noted except possibly in the case of selenium. The 2.5 percent

error estimate is supported by the fact that the maximum spread in the points for any curve was five to six percent.

VI. DISCUSSION AND CONCLUSIONS

The stopping power of copper was studied primarily as a check on the method used for this work, since it already has been reported by Kahn,[14] Chilton,[13] and Madsen.[12] The curves of Kahn and Chilton are about four to six percent apart while Madsen's curve is about 15 percent below them. The present curve lies between the curves of Kahn and Chilton as shown in Fig. 1.

Silver has also been studied by Madsen in the same energy region as the present work. As shown in Fig. 2, our curve lies about eight to ten percent above his.

In the case of gold, most of the data were obtained from three foils. Two sandwich targets were also used. Data from the two types of stopping layers were consistent. The curve shown in Fig. 3 lies about ten percent above Kahn's curve at one Mev and about 25 percent above it at 400 kev. Madsen's results are in essential agreement with Kahn. This is a very disturbing discrepancy since it is far greater than the experimental errors involved. No explanation for the disagreement is advanced.

TABLE IV. Product of stopping power and a factor proportional to proton velocity.

Proton energy (kev)	Element Mn	Cu	Ge	Se	Ag	Sn	Sb	Au	Pb	Bi
400	138	114	112	106	94.8	90.0	92.1	60.8	63.2	65.6
500	137	115	113	109	95.2	90.5	92.9	61.9	63.6	66.6
600	137	118	114	111	93.8	90.2	91.9	62.3	63.7	66.4
700	136	119	115	112	93.0	89.2	90.8	62.7	63.1	65.7
800	135	119	116	112	92.2	89.3	90.2	63.0	62.8	65.0
900	137	118	116	113	93.0	89.2	90.6	63.4	63.1	65.0
1000	136	119	116	115	93.5	88.8	91.2	63.9	64.2	66.2

According to the theories of both Bohr[7] and Lindhard and Scharff,[8] the atomic stopping power σ should be proportional to the reciprocal of the proton velocity. If this is correct, then the product of the velocity and σ should be a constant for a given element. This product is shown in Table IV for the ten elements on which measurements are reported. The product is seen to be roughly constant (within experimental error) for all elements except selenium. In the case of selenium, there was evidence of some physical change, possibly a carbon contamination, which gradually increased the effective thickness of the stopping material.

The theory of Bohr and the theory of Lindhard and Scharff are in disagreement on the dependence of stopping cross section on the atomic number. According to Bohr's theory, σ should be proportional to the cube root of the atomic number for higher values of Z while the theory of Lindhard and Scharff predicts that it should be proportional to the square root. To investigate this, a plot was made of the logarithm of σ as a function of the logarithm of Z. (See Fig. 4.) Included in this plot are data from Kahn,[14] from Dunbar, Reynolds, Wenzel, and Whaling,[15] from Chilton,[13] and from the present work. In cases of duplication where no serious discrepancy occurred, values obtained in this laboratory were used. For krypton, xenon, and gold, two values were included. The slope of the drawn line from hydrogen to argon is about 0.7, while the slope of the line making the best fit from argon to bismuth is about 0.5 as predicted by Lindhard and Scharff.

In Fig. 5, a similar plot is shown of the region from argon to bismuth to give greater detail. Here there seems to be strong evidence of a periodic fluctuation of σ. From hydrogen to argon electrons are added to outer s and p shells, but with scandium the filling of the $3d$ shell beings. Between copper and krypton, electrons are again being added to fill the outer $4s$ and $4p$ shells. The light line on Fig. 5 from copper to krypton has a

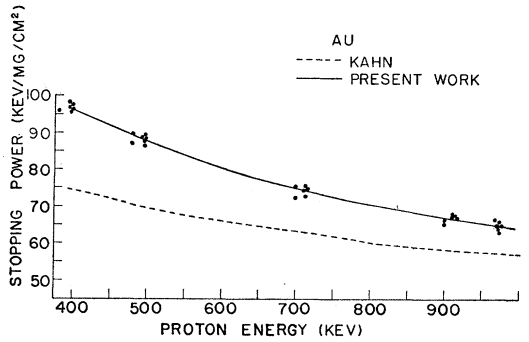

FIG. 3. The stopping power of gold for protons as a function of proton energy. Also plotted is the curve reported by Kahn (see reference 14).

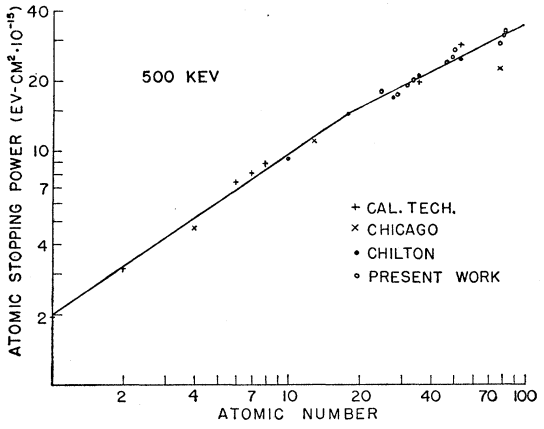

FIG. 4. The atomic stopping cross section σ as a function of atomic number for protons of 500-kev energy. In addition to the data of the present paper there are plotted points from the data reported by Kahn (see reference 14) of the University of Chicago, by Dunbar, Reynolds, Wenzel, and Whaling (see reference 12) of the California Institute of Technology, and by Chilton, Cooper, and Harris (see reference 13).

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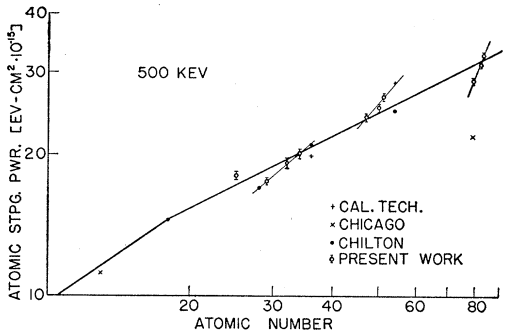

FIG. 5. The atomic stopping cross section σ as a function of atomic number, showing the relatively pronounced rise as the s and p shells are filled.

slope not much different from the line from hydrogen to argon. The same pattern is repeated starting with silver as the $5s$ and $5p$ levels are filled and again starting with gold as the $6s$ and $6p$ electrons are added. However, before too much credence can be given to this periodicity, measurements will have to be made on many more elements. It is interesting that Sternglass[16] has observed a similar periodic variation in the yield of secondary electrons as a function of atomic number when elements are bombarded with high-energy electrons. This is another phenomenon which involves the interaction between the atomic electrons and a high speed charged particle.

It should be noted that if the periodic slope changes as shown in Fig. 5 prove to be valid, then the dependence of the stopping power on the conductivity properties or upon the physical state (solid or gaseous) of an element is probably relatively small.

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Cosine Interaction in CsF and RbF*

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A series of measurements of the line shape of the fluorine resonance *versus* magnetic field have been made using a molecular-beam apparatus. Good theoretical agreement has been found for RbF. The CsF behavior is complicated by the overlapping Cs spectrum. The equivalent field at the fluorine nucleus per unit molecular rotation, H_r, is found to be 2.28 ± 0.20 gauss and 3.00 ± 0.15 gauss for RbF and CsF respectively. These results are less than those previously measured.

I. INTRODUCTION

EARLIER investigations of the fluorine resonance in the alkali fluorides resulted in discrepancies in the determination of the rotational constant c/h which is a measure of the strength of the spin-orbit coupling of the nuclear spin to the molecular rotation. The discrepancies were particularly clear for CsF and LiF. The molecular-beam magnetic-resonance apparatus (MBMR)[1] yielded 18 kc/sec for Li^6F^{19} compared to the value 37 kc/sec for the electrical apparatus[2] (MBER). Similarly, experiments[3] with $Cs^{133}F^{19}$ showed values of 14 ± 2 kc/sec (strong field, MBER) or 14 ± 3 kc/sec (weak field, MBER) compared to 8 kc/sec[1] (MBMR). In addition, the curve shape of the zero field MBMR resonance for CsF did not agree with that predicted from the strong field results. It was therefore decided to repeat the CsF experiments using MBMR including measurements at intermediate fields and to perform a similar experiment using RbF with the possibility of comparison to MBER.[4]

The earlier work was carried out at either high or low fields. Since that time a theory[5] has been conconstructed which predicts the shape of the resonance for all values of the magnetic field in terms of just one parameter. It was hoped that some clue to the discrepancies might be found in the transition from the extreme Zeeman to the complete Paschen-Back conditions. In addition, the verification of the theory has its own intrinsic interest.

II. EXPERIMENTAL DETAILS

Since this experiment was the first to be completed using the new molecular beam apparatus at Berkeley, a brief description of the apparatus will be attempted.

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