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Stopping power of thin solid targets for internal conversion electrons in the energy interval 100-1000 keV

R. Michael Lassise

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STOPPING POWER OF THIN SOLID TARGETS FOR INTERNAL
CONVERSION ELECTRONS IN THE ENERGY INTERVAL 100-1000 keV

by

R. Michael Lassise

B.A., University of Montana, 1974

Presented in partial fulfillment of the requirements for the degree of

Master of Arts

UNIVERSITY OF MONTANA

1977

Approved by:

[Signatures]

Chairman, Board of Examiners

Dean, Graduate School

Date: July 1, 1977

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ABSTRACT


Stopping Power of Thin Solid Targets for Internal Conversion Electrons in the Energy Interval 100-1000 keV (49 pp.)

Director: L. E. Porter

The stopping powers of several materials of low atomic number for electrons with energies between 100 and 1000 keV have been measured. Targets comprised five plastics with average atomic number between 2.5 and 8.0, and aluminum. Monoergic projectiles were obtained from the radioactive sources of $^{139}$Ce, $^{113}$Sn, $^{137}$Cs, and $^{207}$Bi. Energy losses were determined by means of a beta-ray spectrometer. Measured stopping powers were compared with predictions of Bethe-Bloch theory. Whereas the experimental values of stopping power generally were consistent with theoretical predictions, measurements lay always below the Bethe-Bloch curve in the case of the target with lowest atomic number and in cases of foils so thin that energy losses were less than one-fifth of the incident electron energy. However, the present measurements were quite consistent with those of previous experiments in the case of all but two target materials, for which no data was found in the literature.
ACKNOWLEDGMENTS

The author would like to thank W. R. Ellis, M. Baffa, and J. Anderson who made the target mounts and other auxiliary equipment. Also thanks to Dr. Walter Hill who made available the micro-comparator and the electrobalance. And a special thanks goes to Dr. L. E. Porter whose guidance and patience made this project tenable.
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CHAPTER I

INTRODUCTION

In many aspects of physics it is necessary to know how particles interact with each other. On a macroscopic scale one often deals with the subject of stopping power in order to ascertain how much energy is lost by particles traversing a given material. In the present study the stopping power of various thin solid targets for beta-rays (electrons) having incident energies between 100 and 1000 keV has been investigated.

Theoretical stopping power calculations for electrons can be done with the Bethe-Bloch (1933) formula. However, this initial formulation was modified by Halpern and Hall (1948), who introduced the density effect correction, which deals with the density and polarizability of the target. Another improvement came from Rohrlich and Carlson (1954), who extended the Bethe-Bloch formalism to include the positron and also combined all the effects together into one comprehensive formula. The Rohrlich-Carlson version of the Bethe-Bloch formula is used in this paper.

In a recent review by Berger and Seltzer (1967) of the stopping power of matter for beta-rays, it was pointed out that although theory was deemed reliable, experimental results were
limited. Garber, et al. (1971) made a study of aluminum targets for incident energies ranging from 1-4000 eV and found their results consistent with theory. For energies above 1.5 MeV, the study by Westermark (1961) is an example. He dealt with 2.8 MeV electrons incident on targets of low atomic number, including lithium, beryllium, carbon, aluminum, sodium, potassium, silicon, lithium-hydroxide, water, heavy water, benzene, toluene, heptane, and methanol. Westermark (1961) compared his results to theoretical calculations by A. Nelms (1958) and found complete agreement with theory. In a study by Hara (1968) the energy interval investigated fell between the energy intervals mentioned above. He investigated aluminum targets with incident electron energies ranging from 600 to 1200 keV. His stopping power data was within 10% of that predicted by Bethe-Bloch theory. Kalil, et al. (1959) studied very thin aluminum targets in the energy interval 12-127 keV in order to measure stopping power with a calorimetric technique. They found their results to be remarkably consistent with predictions of Bethe-Bloch theory. Other reports of measurements in the interval of 300-1000 keV have been made by McKeen, et al. (1974), Dodd, et al. (1976), and Otten, et al. (1976). Porter (1974) studied the feasibility of the experiment used in this investigation. McKeen, et al. (1974) studied some targets of biological interest at only two energies. Dodd, et al. (1976) and Otten, et al. (1976) investigated some low-Z plastic targets with incident electron
energies of 364, 624, and 976 keV, which correspond to internal conversion electrons from radioisotopes $^{113}\text{Sn}$, $^{137}\text{Cs}$, $^{207}\text{Bi}$, respectively. Although they took only three data points for each target, these limited measurements showed a tendency toward stopping powers larger than those predicted by theory.

The present investigation encompassed the targets of aluminum, a metal, and Mylar®, Kapton®, Hercules N600®, Tryclite®, and Teflon®, which are plastics, in the electron energy interval 100-1000 keV. The data gathered overlaps with that in previously mentioned works (Dodd, et al., 1976 and Otten, et al., 1976) for aluminum, Mylar®, Kapton®, and Hercules N600®. But in all cases the energy interval was extended and more data were gathered for each target material. Teflon® and Tryclite® had not been investigated at all in the interval 100-1000 keV prior to this study. After the data was acquired, it was compared against theoretical computations based on the Bethe-Bloch formula. A computer code was devised for this purpose (see App. I). Other workers have also performed similar computations: Berger and Seltzer (1967), L. V. Spencer (1955), and A. Nelms (1956 and 1958). All four of these calculations use the same Bethe-Bloch formulation but different values of the mean excitation energy, which is the only major parameter of the formulation independent of projectile energy.

The experimental setup was the same as described by McKeen, et al. (1974). The calculations used to reduce the experimental data were accomplished using a method set forth by Bichsel (1972)
with modifications and some original calculations by the author (Porter, 1976). All measurements and calculations were performed by the author.
CHAPTER II

EXPERIMENTAL METHOD

This particular experiment was divided into two parts: measurement of the target areal density and measurement of the energy loss. The parts are separate and distinct but together they constituted the experimental procedure.

The areal density was ascertained by measuring the area of a specific target material sample and then weighing the sample. Then the areal density was obtained by dividing the mass by the area, with resulting units of gm/cm$^2$. Although the general method was simple, different sets of equipment were used to ascertain the areal density. The reason for use of these different methods was that as the experiment progressed, equipment capable of greater accuracy was deemed necessary and therefore was located and utilized.

The areal density for aluminum targets was found in the following manner. Circular targets the size of the target holders (≈2 cm. diameter) were cut out using a cork borer. The target's diameter was then measured on a travelling microscope while making sure that the measurement was of the full diameter, by utilizing different orientations of the target. The travelling microscope could be read to $10^{-4}$ cm. Three independent measure-
ments were made and the average of the three was taken. Also care was taken not to produce errors by slack in the screw of the travelling microscope (i.e., backlash). The mass was ascertained by using an analytical balance whose reproducibility was within 1 mgm. Care was taken to balance the instrument before use and to check it after the measurement was made. Again three independent measurements were made and then averaged. The maximum uncertainty in areal density for the aluminum was 3%. Later in the experiment a thinner foil of aluminum was found and it was measured in much the same way as above except that an electrobalance could be read with a reproducibility of $10^{-5}$ gm. The uncertainty of measurement was reduced to 1%. After measuring the areal density the target was mounted on the target holder and held in place by glue. Care was taken not to get glue on the surface to be exposed to the radioactive source. Gloves were worn to keep oil from the fingers from becoming part of the target. If glue or oil got on a target, the target was discarded and the whole process was started again. Another factor to be considered was the flatness of the target. This property was ensured by putting a glass plate on the target while the glue was drying. This method worked well for the aluminum target.

The method of measuring areal density of the rest of the targets differed from the method used for the thicker aluminum targets. The method was similar to that used for the thinner foil of aluminum in which a travelling microscope and an electrobalance were utilized. A difference was that square rather than circular pieces of the material.
were cut out and measured. After the areal density had been determined, circular targets were cut from the material and mounted as was the aluminum. Toward the end of the experiment thinner targets for Mylar® and Kapton® were needed; their areas were found using a microcomparator which could be read to \(10^{-5}\) cm. Therefore the uncertainties in areal density for these materials will be divided into the categories, "normal" for the travelling microscope and "thin" for the microcomparator. For Mylar® the largest uncertainties incurred were, for normal, < .01% and for the thin, .8%. For Kapton® the normal's maximum uncertainty was < .01% and the thin's maximum uncertainty .08%. For Hercules N600® and Teflon®, the maximum uncertainty was < .01%. The Trycite's® maximum uncertainty in measurement was 1.3%. The flatness of the mounted targets was good except for Trycite®. Trycite's® flatness worsened as the thickness was increased. Discussion of this problem will be conducted in the Analysis and Results Section.

Measurement of energy loss was carried out using a beta-ray spectrometer. Attached to the beta-ray spectrometer were the following pieces of equipment for control and measurement. A well-regulated D. C. power supply with a maximum current of 1.5 amps was used to control the current to the magnet of the beta-ray spectrometer. The current was measured on an ammeter which could be read to .002 amps. The scale extended from 0 to 1.5 amps. For counting events from the radioactive sources a Geiger-Muller tube connected to a scaler was used. To find how many events happened in a specific amount of time, a chrono-
meter which read to .1 sec was used. Evacuation of the chamber in
the beta-ray spectrometer was achieved with a pump which reduced the
pressure of the chamber to about \(10^{-6}\) mm Hg. Figure 1 gives a block
diagram of the equipment setup. Inside the chamber a slit was placed
to provide resolution in energy. Two different slits were used:
Slit #1 and Slit #2. Slit #1 provided an energy resolution of 6% and
Slit #2 a resolution of 4% (see Figure 2). After each run the beta-
ray spectrometer was degaussed in order to rid the magnet of residual
magnetism.

To measure energy loss with this technique one must have and
know a specific initial energy. This end was accomplished by the use
of internal conversion electrons from radioactive sources whose act-
ivities were 10 microcuries. The sources were \(^{113}\)Sn, \(^{139}\)Ce, \(^{137}\)Cs,
and \(^{207}\)Bi. For the corresponding energies see Table I.
FIGURE 1

EXPERIMENTAL SETUP

FIGURE 2

SLIT CONFIGURATION

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### TABLE I

**ENERGIES FOR RADIOACTIVE SOURCES**

<table>
<thead>
<tr>
<th>Sources</th>
<th>Energy (keV)</th>
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<tbody>
<tr>
<td>$^{139}$Ce (Cerium)</td>
<td>126</td>
</tr>
<tr>
<td>$^{139}$Ce (Cerium)</td>
<td>159</td>
</tr>
<tr>
<td>$^{113}$Sn (Tin)</td>
<td>364</td>
</tr>
<tr>
<td>$^{137}$Cs (Cesium)</td>
<td>624</td>
</tr>
<tr>
<td>$^{207}$Bi (Bismuth)</td>
<td>976</td>
</tr>
</tbody>
</table>
CHAPTER III

THEORY

The well-known Bethe-Bloch formula for electrons is based on the assumption that the collision of the incident electron and the target is a relativistic free electron-free electron collision which evinces the Møller cross section. In this case, the maximum energy transfer is 1/2 since electrons are indistinguishable from each other. The results of the derivation of Rohrlich and Carlson (1954) are as follows. For a certain minimum relative energy transfer, \( \varepsilon_1 \), where \( \varepsilon_1 \) greatly exceeds the ionization potential of the material, the average energy loss per atom due to collision is

\[
Z \int_{\varepsilon_1}^{1/2} \varepsilon (d\sigma/d\varepsilon) \, d\varepsilon = Z \chi \left[ \ln \frac{1}{4 \varepsilon_1} + 1 - \frac{2 \gamma - 1}{\gamma^2} \ln 2 + \frac{1}{8} \left( \frac{\gamma - 1}{\gamma} \right)^2 \right]
\]

where \( Z \) = atomic number of the target,

\[
\frac{d\sigma}{d\varepsilon} = \text{Møller differential cross section, i.e.,}
\]

\[
\frac{d\sigma}{d\varepsilon} = \frac{\chi}{T} \left[ \frac{1}{\varepsilon^2} + \frac{1}{(1 - \varepsilon)^2} + \left( \frac{\gamma - 1}{\gamma} \right)^2 - \frac{2 \gamma - 1}{2 \varepsilon (1 - \varepsilon)} \right]
\]

\[
\chi = \frac{2 \pi r^2 m c^2}{\beta^2} \text{ where } \beta = \frac{v}{c} \text{ and } r^2 = 7.94030 \times 10^{-26} \text{ cm}^2.
\]

\[
\gamma = \frac{m'}{m} \text{ for } m' \text{ the relativistic mass and } m \text{ the rest mass of the electron,}
\]
\[ T = \text{kinetic energy of the incident electron} = (\gamma - 1)mc^2, \]
\[ mc^2 = \text{rest mass energy of the electron} = 510.956 \text{ keV}, \]
\[ \varepsilon = \text{energy transfer}--- \text{a dimensionless quantity given in units of } T. \]

In obtaining the above solution it is assumed that \( \varepsilon_1 \) is much less than 1 so all \( \varepsilon_1^2 \) and higher order terms are dropped. For the low energy transfer (\( \varepsilon < \varepsilon_1 \)) where the incident energy is near the ionization potential, one has

\[
ZT \int_{\varepsilon_0}^{\varepsilon_1} \varepsilon \left( \frac{d\sigma}{d\varepsilon} \right) d\varepsilon = 2\chi \left[ \ln \frac{2T^2\varepsilon_1(\gamma + 1)}{I^2} - \beta^2 \right]
\]

where \( I \) is the mean excitation energy. This integral solution comes from an explicit summation over the various excitation probabilities of the atoms of the material since the free electron-free electron collision assumption no longer holds. Now the average collision loss per unit path length for \( N \) atoms becomes

\[
- \left[ \frac{d\varepsilon}{dx} \right] = NZ\chi \left[ \ln \frac{T^2(\gamma + 1)}{2I^2} + f^-(\gamma) \right]
\]

where \( f^-(\gamma) = 1 - \beta^2 - \frac{2\gamma - 1}{\gamma^2} \ln 2 + \frac{1}{8} \left( \frac{\gamma - 1}{\gamma} \right)^2 \)

This equation arises from the addition of the above two solutions of the above integrals. For the positron aspect of the theory the assumptions are the same except that the maximum energy transfer is now 1 rather than 1/2 and the cross section used becomes the Bhabha cross section. Following the same procedure as for the electron,
the Bethe-Bloch formula becomes

\[- \left( \frac{dE}{dx} \right)^+ = N \chi \left[ \ln \frac{T^2(y+1)}{2I^2} + f^-(\gamma) \right] \]

where \( f^+(\gamma) = 2 \ln 2 - \frac{\beta^2}{12} \left[ 23 + \frac{14}{\gamma+1} + \frac{10}{(\gamma+1)^2} + \frac{4}{(\gamma+1)^3} \right] \).

The formulae above only take into account the collision aspect of the theory, which is the predominant effect. Other effects are the Bremsstrahlung effect and the density effect. The Bremsstrahlung or radiation effect below 2 MeV has been calculated by Berger and Seltzer (1967) to be less than 1%, and therefore negligible for our purpose. A derivation of the magnitude of this effect can be found in Bethe and Ashkin (1953). The density effect, which is due to polarizability and density of the target material, is small but not negligible. The density effect, first proposed by Fermi (1940) and later incorporated into Bethe-Bloch theory by Halpern and Hall (1948), must therefore be put into the formula for stopping power as follows,

\[- \left( \frac{dE}{dx} \right)^- = N \chi \left[ \ln \frac{T^2(y-1)}{2I^2} + f^+(\gamma) - \delta \right] \]

where \( \delta = \) density effect correction. Sternheimer (1956) has carried out extensive studies of the density effect by considering the oscillator strengths for the various materials. Sternheimer's formulae for the density effect correction are

\[ \delta = 4.606X + C + A(X_1 - X)^n \] when \( X_0 < X < X_1 \)

\[ \delta = 4.606X + C \] when \( X > X_1 \)
where $X = \log_{10} \left( \frac{p}{mc} \right) = 0.21715 \ln \left( \frac{\beta^2}{(1-\beta)^2} \right)$. Here $p$ is the momentum of the incident particle, and $A^*, n, C, X_1, X_0$ are constants which have been evaluated for a given material. The constants are calculated from a knowledge of the oscillator strengths of the substance, which implies that these constants are linked to the mean excitation energy.

The mean excitation energy is known if the oscillator strengths are known. However, for substances more complicated than hydrogen or helium the oscillator strengths are not well known. Therefore the mean excitation energy is usually found experimentally from massive projectile stopping power and range studies. Some of the values of mean excitation energy used in this study came from the deuteron and alpha particle investigation of Shepard and Porter (1975). When the mean excitation energy of a substance could not be obtained from such experimental studies, the mean excitation energy was calculated using Bragg's rule for the additivity of stopping effects.

$$\ln I_b = \sum_{i} n_i Z_i \ln \frac{I_i}{\sum_{i} n_i Z_i} ,$$

where the index $i$ refers to the $i^{th}$ constituent and $n_i$ is the atomic concentration of the $i^{th}$ constituent (Porter, 1975). The composition of Hercules N600®, Kapton®, Mylar®, Trycite®, and Teflon® must be known in order to calculate the theoretical stopping power. The makeup of Hercules N600®, a polypropylene homopolymer, is C$_3$H$_6$. Kapton®, a polyimide made by a condensation reaction between a polyamic acid and aromatic amine, consists of 22 C, 10 H, 2 N, and 5 O.
Mylar® is a polyester film, consisting of \( C_{10}H_8O_4 \). Trycite® is a polystyrene composed of CH. Teflon® is composed of \( C_2F_4 \). The dispersion of values for the mean excitation energy found in the literature can be quite large. For example, the mean excitation energy for aluminum used in this investigation was 162.5 eV, which agrees with that used by Berger and Seltzer (1967) and A. Nelms (1958). However, in earlier studies L. V. Spencer (1955) and A. Nelms (1956) cited 150 eV as the correct value. In a review of then current problems in stopping power, Fano (1967) listed the uncertainty of mean excitation energy values as a major source of concern. Therefore, when comparing theory and experimental data the choice of mean excitation energy for inclusion in Bethe-Bloch calculations is very important. The values chosen for Mylar® and Teflon® were based on measurements by Shepard and Porter (1975). The value of \( I \) adopted for aluminum was that of Bichsel (1972). The mean excitation energy of Trycite® was that derived from yet unpublished measurements of stopping power for protons (Porter, 1977). Since no experiment-based values of \( I \) were available for Hercules N600® and Kapton®, the values used were those obtained from Bragg's rule of additivity, but increased by 10% to reflect the general trend in observed departures from Bragg's rule by low-Z target materials (Shepard and Porter, 1975). The constituent mean excitation energies employed in the Bragg's rule calculation were those of Fano (1963). Table II gives a listing of \( I \), along with average atomic number (\( \bar{Z} \)) and average atomic weight.
(Å), for various target materials and Table III gives calculated Bethe-Bloch stopping power as obtained from the computer code (see App. I).
### TABLE II

VALUES FOR THE TARGETS

<table>
<thead>
<tr>
<th>Targets</th>
<th>I (eV)</th>
<th>Z</th>
<th>A</th>
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<tr>
<td>Hercules N600 ®</td>
<td>26.8</td>
<td>2.667</td>
<td>4.676</td>
</tr>
<tr>
<td>Trycite ®</td>
<td>71.1</td>
<td>3.500</td>
<td>6.509</td>
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<tr>
<td>Mylar ®</td>
<td>81.0</td>
<td>4.540</td>
<td>8.740</td>
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<td>Kapton ®</td>
<td>83.9</td>
<td>5.026</td>
<td>9.804</td>
</tr>
<tr>
<td>Teflon ®</td>
<td>119.6</td>
<td>8.000</td>
<td>16.670</td>
</tr>
<tr>
<td>Aluminum</td>
<td>162.5</td>
<td>13.000</td>
<td>26.984</td>
</tr>
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<table>
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<tr>
<th>Incident Energy (MeV)</th>
<th>Hercules N600®</th>
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<tr>
<td>.050</td>
<td>7.77</td>
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CHAPTER IV

DATA ACQUISITION

The energy loss data for this experiment were taken from graphs (spectra) obtained with a specific target in place or with no target at all, and a given source. On these graphs counting rate was plotted against magnet current. At a particular current the scaler counter was allowed to run for a minimum of three minutes. The counter was then stopped and its reading was divided by the time elapsed and then plotted on the graph for the appropriate magnet current. After the spectrum was completed it was noted that a peak existed. This peak corresponded to a certain electron energy, but magnet current determined the magnetic field which measures the electron momentum. Therefore a conversion from a momentum spectrum to an energy spectrum was necessary, since stopping power is obtained from the average energy loss and target areal density. Then a centroid calculation was made, using a computer code (see App. I), taking into account the beginning and end of the peak and the background radiation level of the source.

Since the choices of beginning and end of a peak were only most probable choices a check was made as described in the Analysis and Results Section. The source energies must be known in order to calculate the stopping powers. The source energies were obtained
CHAPTER V

CALCULATIONS

In the reduction of experimental data several sequential calculations were necessary. The first calculation was that of the areal density of the target material which required division of the target mass by its area. Second, it was necessary to obtain the average electron energy by centroid calculation for the electron energy spectrum. For a derivation of the relationship between momentum and energy spectra see Appendix II. The centroid is characterized by a value of the relativistic parameter, \( \omega = \frac{T}{mc^2} \), corresponding to the centroid, \( \bar{\omega} \). On the peaks beginning and end they were picked at the points deemed to be the most probable locations. Once a centroid value, \( \bar{\omega} \), was found the average energy was determined by multiplying \( \bar{\omega} \) by 510.956 keV. Third, this energy was subtracted from the known energy of the radioactive source to obtain the energy loss, \( \Delta T \). Fourth, the stopping power was calculated by dividing the energy loss by the areal density.

The calculation to this point has assumed that the electron travels in a straight line while traversing the target, when in fact the electron travels a very tortuous path. The source of this effect is the multiple scattering of the electron while traversing the target material. Therefore a "Path Length Rectification" factor (PLR) was applied to the stopping power. The derivation by
Garber, et al. (1971) is given in Appendix II. PLR is given by

$$PLR = 1 + \frac{\Lambda}{3t},$$

where

$$\Lambda = \frac{2\pi N \rho t^2 r^2 (Z+1)}{A} \left[ \ln \left( \frac{137\beta}{Z^{1/3}(1-\beta^2)^{1/2}} \right) + \ln 1.76 - (1 + \frac{\beta^2}{4}) \right],$$

where $t =$ thickness of target,

$N_a =$ Avogadro's number

$\rho =$ density of target

$Z =$ atomic number of the target, and

$r^2 = 7.94030 \times 10^{-26} \text{ cm}^2.$

One additional calculation was that of $T_c$. $T_c$ is the energy at which stopping power is evaluated. $T_c$ represents the energy of the source less half the energy loss in target traversal.

In every experiment uncertainties must be considered. The overall uncertainty in stopping power was

$$\frac{\Delta S}{S} = \left[ \left( \frac{\Delta m/A}{m/A} \right)^2 + \left( \frac{\Delta (\Delta T)}{\Delta T} \right)^2 + \left( \frac{\Delta \text{PLR}}{\text{PLR}} \right)^2 \right]^{1/2}$$

with the dominant error coming from the $\Delta T$ term.

In Appendix III a sample calculation is given for an aluminum target and a tin source ($^{113}\text{Sn}$).

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CHAPTER VI

ANALYSIS AND RESULTS

When one views the plots of the experimental data with the theoretical curve overlaid an extremely good average fit is achieved (see Fig. 5-A to F). For every target, however, anomalous data points occur. These points seem to correlate with energy losses of less than 20% of the source energy (see Table IV-A to F). This correlation holds at the high energy end of the interval since all measurements lie below theoretical calculations and all of the energy losses less than 20% of the source energy. Hercules N600® seemed to have all its measurements lying below the theoretical curve. However, data points with energy losses greater than 20% are within a standard deviation of the curve. The aluminum data obtained in the present study filled the gap between the Hara (1968) data and the Kalil, et al. (1959) data, and was in agreement with the findings of both investigators. This corroboration leads one to believe that the results of the present study are valid. The data acquired for Hercules N600®, Kapton®, and Mylar® could have been compared with that reported by Dodd, et al. (1976) and Otten, et al. (1976). However, an error was discovered in their calculations (Porter, 1977). Therefore the latter calculations were corrected and the resulting data corroborated the findings of the present investigation. Moreover Dodd, et al. (1976)
investigated Hercules N400®, which is a polyethylene-polypropylene copolymer with 4% ethylene, but has the same atomic number, atomic weight and mean excitation energy as Hercules N600®. Otten, et al. (1976) investigated, along with Mylar® and Kapton®, Melinex®, which is chemically identical to Mylar® but made by a different company.

As data was being gathered two questions were posed. The first was related to reproducibility of data and the second was one mentioned by Chen and Warshaw (1951).

Chen and Warshaw (1951) questioned whether the edge effect of foils—an effect which produces large distortion of a spectrum by inclusion of edge energy losses—was causing measurements of stopping power to be higher than if only the energy losses from the center of the foil were measured. This effect would be greatest at lower energies by virtue of the increased probability of large angle electron scattering at these energies. The problem was attacked in the following manner. A baffle (see Fig. 3) which would leave the center of the target exposed but block the edges, and thus cut the area exposed to the source by about half, was placed over the radioactive source. This adjustment voided the target edge effects. Measurements were made for the low energy source ($^{139}\text{Ce}$) and the edge effect was found to be less than 1%, well within the uncertainty of the experiment.

Reproducibility was checked periodically throughout the experiment. Reproducibility was not tested for all targets but was tested for electrons from every source in every material. A deviation of less than 1% was found, well within experimental uncertainty.
FIGURE 3

DIAGRAM OF EDGE EFFECT TEST SETUP

TOP

Source

Baffle

Baffle & Source

SIDE

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Another problem arose with the Trycite® targets. The problem was one of an inability to attain flat targets. The effect was noted to be a cosine effect and a deviation of 5 degrees from flatness was estimated by direct viewing. Although this problem is not insignificant for the areal density, it is a small effect compared to the $\Delta T$ uncertainty and therefore is considered to be a second order effect since $\Delta T$ is the dominant term in the uncertainty of stopping power. No correction for the deviation from flatness was introduced into stopping power calculations.

The principal uncertainty in the data centered around determination of the centroid location. The choices were somewhat arbitrary a check was made. In Figure 4 the most probable locations for start and end are marked A and B, respectively. Now the starting point could be shifted to C or D and the end point shifted to E or F. By doing this a slight shift is noted in the centroid value, $\bar{w}$. Another problem in calculating the centroid was in deciding the background level. One could take the normal radiation background from the source to be uniform and calculate $\bar{w}$, or one could choose a sloping background as shown in Figure 4 and then calculate $\bar{w}$. This alteration in assumed background also produces a shift in $\bar{w}$. The largest shift induced by these tests was used in the calculations of the uncertainty in $\Delta T$. 

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FIGURE 4

CURRENT PEAK

Sloping Radiation Level

Background Radiation Level

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### TABLE IV-A

**EXPERIMENTAL DATA FOR HERCULES N600**

<table>
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<tr>
<th>$\bar{T}$ (keV)</th>
<th>$m/A$ (mgm/cm²)</th>
<th>$\Delta T$ (keV)</th>
<th>$T_C$ (keV)</th>
<th>$S_\alpha$ (MeV·cm²/gm)</th>
<th>PLR</th>
<th>$S(\text{MeV·cm}^2/\text{gm}) + \Delta S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>94.4</td>
<td>8.05</td>
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<td>110.2</td>
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<td>21.94</td>
<td>21.1</td>
<td>353.5</td>
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<td>1.015</td>
<td>.95±.04</td>
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## Table IV-B

**Experimental Data for Trycite**

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<th>$T_n$ (keV)</th>
<th>$S_n$ (MeV·cm²/gm)</th>
<th>PLR</th>
<th>$S$(MeV·cm²/gm)±ΔT</th>
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### Table IV-D

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<td>$\Delta T$(keV)</td>
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### TABLE IV-F

EXPERIMENTAL DATA FOR ALUMINUM

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<th>T_c (keV)</th>
<th>S_0 (MeV·cm²/gm)</th>
<th>PLR</th>
<th>S(MeV·cm²/gm) ± ΔS</th>
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<td>316.1</td>
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<td>888.1</td>
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<td>1.065</td>
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</tbody>
</table>
**FIGURE 5-A**

HERCULES N600 Ø

- Present Investigation
- Hercules N600 Ø; Dodd, et al. (1976)
- Hercules N400 Ø; Dodd, et al. (1976)

![Graph showing the relationship between S (MeV-cm²/gm) and Tc (keV).]
FIGURE 5-B

TRYCITE®
FIGURE 5-C

Mylar®

- Present Investigation
- Melinex®; Otten, et al. (1976)
- Mylar®; Otten, et al. (1976)
FIGURE 5-F

ALUMINUM

○ Present Investigation
△ Kalil, et al. (1959)
□ Hara, (1968)
CHAPTER VII

CONCLUSIONS

The energy loss data generally agrees with Bethe-Bloch theory, except when the energy loss was less than 20\% of the source energy. The aluminum data seemed to be in full agreement with previous works (Hara, 1968 and Kalil, et al., 1959). The other target materials seemed to agree with the theory except in the case of Hercules N600, which yielded stopping powers consistently below theoretical calculations. However, when energy losses were 20\% or more for the Hercules N600, stopping powers were within one standard deviation of Bethe-Bloch theory. Therefore, in general it was thought that experimental data seemed to corroborate the Bethe-Bloch theory. An exception was Hercules N600 material, for which measurements lay considerably lower than calculated values over the entire energy interval -- a result which remains as yet inexplicable.
LIST OF REFERENCES


APPENDIX I
THIS IS A STOPPING POWER CALCULATION CODE
FOR ELECTRONS AND POSITRONS. THE CODE HAS THE
FOLLOWING DEFINED QUANTITIES.
\( \gamma = \frac{\text{ENERGY}}{\text{VOLUME}} \)
\( \text{TAN} = \text{KINETIC ENERGY IN NUCLEI} \)
\( \text{BUT PUT TAN IN AS HOW IT IS CONSTRUCTED} \)
\( \text{EARTH} = (\gamma / \gamma) \)
\( \text{Z = ATOMIC NUMBER} \)
\( \text{A = ATOMIC WEIGHT} \)
\( \text{PROPORTION OF MATERIAL IN Gy/Hr} \)
\( \text{T= MEAN EXCITATION ENERGY AND IS GIVEN ANY WAY POSSIBLE} \)
\( \text{OUT INTO PROGRAM AC %-V} \)
\( \text{EFFICIENCY CORRECTION FACTOR AND IS SHOWN HOW TO GET} \)
\( \text{IN THIS PAPER, THE ATOMIC TABLE IS RECOGNIZED AND THE} \)
\( \text{PARAMETERS ARE EITHER DEFINED OR GIVEN IN THIS PAPER.} \)

TYPE 5

FORMAT (' , ENTER 7, A, REC, IT')
ACCEPT 7,7, A, RHO, IT

FORMAT (4F)

TYPE 6

FORMAT (' , ENTER X, Y, A, 1')
ACCEPT 9, Y1, X, A, 1

FORMAT (5F)

EN = 510.956

TYPE 7

FORMAT (' ELECTRON AND POSTRON?')
ACCEPT 15, J

FORMAT (15)

TYPE 17

FORMMAT (' ENERGY STOPPING POWER')

UNIT = 0
ON AS L = 1, 2, 6
UNIT = 360 T
TAU = UNIT / 610.956
DATA = 0.0 (TAU (TAU + 2) / (TAU + 1))
Y = 1
1 = 0.5
GCEL = (1.0 / (X T Y1, Y, A, 1, 1, 1))
T 1 = .117505
FOR T = 0 TO TAU + 1
GOTO 5
5 GOTO (DATA, TAU)
5 FOR Y = 0 TO (TAU + 2) (TAU + 2) / (2 * (UNIT / EN) + 2) + 3.01
END = (DATA + 2)
SEND
T 1 = .117505
GOTO 5
9 TYPE 20, UNIT, 5

FORMAT (6F)

GOTO 10

8 TYPE 20, UNIT, 5

FORMAT (2F)

CONTINUE

TYPE 97

FORMAT (A, 1, FT, 10, A, GCEL)

TYPE 99, FT, GO: L

TYPE 105

100 FORMAT (' DO YOU WISH TO CONTINUE? I=YES, 0=NO')
ACCEPT 11, 11

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FUNCTION ERG (G, TA)
G = G * LOG
SP = CY * (T + 4) / (TAI + 2) * 2.4 / (TAI + 2) ** 2.5
FF = SP / 1.2
RETURN
END
FUNCTION ERG (G, TA)
F = 1 - VTA ** 2 * (TAI + 2) ** 8 * (KTAI + 1) ** LOG10 / (TAI + 1) ** 2
RETURN
END
FUNCTION FGL (G, TA, Y1, Y2, C, V1, V2)
Y1 = Y1 ** 15 ** LOG (1 - GTA ** 2) / (1 - GTA ** 21)
IF (V1, G, V1) GO TO 110
IF (V2, G, V2) GO TO 120
FL = Y1 ** 8 ** 17 ** 1 * (Y1 - Y2) ** 8 * 1
GO TO 100
1 10 FGL = 4.56 ** C
GO TO 110
1 20 FGL = 0
1 30 RETURN
END
THIS PROGRAM IS DESIGNED TO TAKE
RAW DATA FROM EXPERIMENT AND GIVE A CENTROID
IN THE CALCULATION OF ENERGY AND THEN
GIV TH LN LOOP FOR ENERGY.
ENDTHS MEAN OF TARGET IN UG/CM**2
TMT=SOURCE ENERGY LN KEY
TMT AND TMT IN KEY BUT S AND SPOD IN UG/CM**2/CM
XY,YY ARE THE POINT JUST PRIOR TO THE STARTING POINT
OF THE PEAK AND XX,YY IS THE POINT JUST AVER THE
ENDING POINT OF THE PEAK.

TYPE 5
FORMAT (" ENTER THE NUMBER OF POINTS")
ACCEPT 16, NX
FORMAT (4)
DIM M(N), X(N), Y(N)
DIM 1 (N)
FORMAT (3)(
DO 21 M=1,NX
111=M=N
CMFA(M)=FORMAT (MYY)
111 CONTINUE
TYPE 26
FORMAT (" ENTER BACKGROUND")
ACCEPT 29, RG
FORMAT (4)
SX=0
TY=0
SN=0
Xn=0
DO 50 J=2,NX
S=X(J)-S
Xn=XJ(1)-S
Yn=(CMFA (J)-CMFA (1)) * CMFA (J)
SY=SY+Xn
TY=TY+Yn
111 CONTINUE
CMFA=TV/SY+CMFA (1)
TYPE 50
FORMAT (" " CMFA= ', ')
TYPE 70, CMFA
111 FORMAT (F)
TYPE 121
121 FORMAT (" INPUT INITIAL ENERGY,AP-AL DENS.,&LOP")
T=CMFA * 510.956
ACCEPT 124, TINT, RHO, DLO
124 FORMAT (5)
TINT=TINT-T
TINT=TINT-TINT
S=TDI/IND
SPL=SD/PLP
TYPE 125
125 TYPE 126, S, SPL, TDL, TINT
FORMAT (" "
126 FORMA(IF, C', Y', F, Y', Y', F)
A=M* (Y(N)-Y (1))/ (YT(Y N)-Y (1))
Y=1
NY=0
N=Y/(NY)
DO 141 K=2,NX
C(X) = 3M \times X(T) - T
T(XY) = Y (K)
Z(X) = 4FEG \times (X) - 3FEG \times (1) \times X
W = ZT \times W
Z = XN \times X

1 40
CONTINUE
END

1 50
FORMAT (0, INPUT, \#,\#) \#,
ACCEPT \#, \# \#,
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TYPE 390
FORMAT('T', 10, 6, TPR, TPR)
TYPE 391, FORMAT, TPR, TPR
330  FORMAT('T, M, E, 3Y, B')
TYPE 530
530  FORMAT('4 DO YOU WISH TO CONTINUE? Y=1, N=0')
ACEPER 540, T
540  FORMAT(T)
IF (T.EQ.1) GO TO 4
END
FUNCTION F(X, I)
F = SQRT((X, 3) ** 4 + 1) - 1
RETURN
END
APPENDIX II
\[ \eta = \frac{p}{m_0 c} = \frac{e r B}{m_0 c} = C^* i \]

where \( C^* \) is a constant

\( i \) is current

\( e = 1.60 \times 10^{-19} \) coul.

\( r \) = effective radius and

\( B \) = magnetic flux density

Now

\[ \omega = \sqrt{\eta^2 + 1} - 1 \quad \text{where} \quad \omega = T/m_0 c^2 \]

therefore

\[ \omega = \sqrt{(C^* i)^2 + 1} - 1 \]

\( C^* \) is an unknown constant. It was found by taking the average current for unretarded \(^{207}\text{Bi}\) peaks, where \( \eta = \omega \) giving \( C^* \) an average value of (3.505 ± 0.001) amps\(^{-1}\).

Therefore

\[ \omega = \sqrt{(3.505 i)^2 + 1} - 1 \]
If all electrons are considered irrespective of their displacement or angle of emergence, the average increase in path length, $\bar{\Lambda}$, is

$$\bar{\Lambda} = t^2/w^2$$

where $t$ is thickness of target material and $w^2$ is a dimensionless parameter defined by

$$w^2 = 4t<\theta^2>$$

Here $<\theta^2>$ is the mean squared scattering angle, which has been calculated by Ritchie, et al. (1968):

$$<\theta^2> = \frac{8\pi N_a t^2 r^2 Z(Z+1) \rho}{\bar{A}} \frac{1-\beta^2}{\beta^4} \left[ \ln \frac{137\beta}{z^{1/3}(1-\beta^2)^{1/2}} + \ln 1.76 - (1 + \frac{\beta^2}{4}) \right]$$

where $\rho = \text{mass density of the target}$,

$N_a = \text{Avagadro's number}$,

$r^2 = 7.904030 \times 10^{-26} \text{ cm}^2$,

$Z = \text{Atomic number of target}$,

$\bar{A} = \text{atomic weight}$, and

$\beta = v/c$

Then $\bar{\Lambda} = t<\theta^2>/4$, and

$$\frac{\bar{\Lambda}}{t} = \frac{2\pi N_a \rho tr^2 Z(Z+1)}{\bar{A}} \frac{1-\beta^2}{\beta^4} \left[ \ln \frac{137\beta}{z^{1/3}(1-\beta^2)^{1/2}} + \ln 1.76 - (1 + \frac{\beta^2}{4}) \right]$$

Now if only the particles which leave the absorber nearly perpendicularly were detected, which was the case in this investigation, then PLR becomes

$$\text{PLR} = 1 + \frac{\bar{\Lambda}}{3t}$$

as shown by Yang (1951).
Sample Calculation

\[ m = 30.333 \text{ mgm} \quad \text{Area} = A = 1.2975 \text{ cm}^2 \]

Areal density = \( \frac{m}{A} = 23.376 \times 10^{-3} \text{ gm/cm}^2 \)

Now every current of the peak must be converted to a corresponding electron energy parameter, \( \omega \), where

\[ \omega = \sqrt{(C\beta i)^2 + 1} - 1 \]

Then a centroid value is found which gives

\[ \overline{\omega} = .630 \]

\[ \overline{T} = .630 \times 510.956 \text{ keV} = 322 \text{ keV} \]

\[ \Delta T = \overline{T}_{\text{source}} - \overline{T} = (364 - 322) \text{ keV} = 42 \text{ keV} \]

\[ T_c = \overline{T}_{\text{source}} - \Delta T/2 = 343 \text{ keV} \]

Now

\[ S_0 = \frac{\Delta T}{m/A} = \frac{42 \text{ keV}}{23.38 \times 10^{-3} \text{ gm/cm}^2} = 1.80 \frac{\text{MeV-cm}^2}{\text{gm}} \]

Then we calculate PLR

\[ \text{PLR} = 1 + \overline{\Delta}/3t \]

\[ \overline{\Delta}/3t = \frac{2\pi a_r \rho t}{3A} Z(Z+1) \left[ \ln \left( \frac{137 \beta}{2^{1/3} (1-\beta^2)^{1/2}} \right) + \ln 1.76 - (1+\beta^2/4) \right] \]

\[ \overline{\Delta}/3t = \frac{.302}{2} \frac{23.38 \times 10^{-3}}{26.982} \frac{13(14)}{13(14)} \frac{1-.8176^2}{.8176^2} \left[ \ln \frac{137 \times .8176}{13^{1/3} (1-.8176^2)^{1/2}} + .56531 \right] - (1+\frac{.8176^2}{8}) \]

\[ \overline{\Delta}/3t = .045 \]

\[ \text{PLR} = 1+.045 = 1.045 \]

\[ S = S_0/\text{PLR} = \frac{1.80}{1.045} = 1.72 \frac{\text{MeV-cm}^2}{\text{gm}} \]