# The Specific Primary Ionization and Energy Loss of Fast Electrons in Matter*

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By utilizing the dependence of the efficiency of a Geiger-Mueller counter upon the primary ionization of a counted particle, the primary ionization by electrons in hydrogen has been determined for energies in the range 0.2 Mev to 9.0 Mev. The relative stopping powers of carbon and $H_2O$ have also been investigated, the results yielding evidence for the existence of a polarization effect which reduces the energy loss of fast particles in condensed matter. Experimental results are compared with those of the Bethe-Bloch theory and the Halpern-Hall theory which takes into account the polarization properties of the medium.

## INTRODUCTION

In its passage through matter a charged particle creates ion pairs through the ejection of secondary electrons from the molecules in the vicinity of its path. These secondaries may in turn produce ionization; consequently, it is possible to define a *primary* and a *total* specific ionization. Cloud-chamber studies have led further to the specification of a *probable* ionization, defined as the number of ion pairs per cm exclusive of ions in clusters greater than a certain upper limit. It is also possible, however, to count the *primary* ion pairs by expansion of the chamber immediately after the passage of a particle.

Collision theory in its present state predicts a variation of both primary and total ionization roughly as follows. At low energies the ionization decreases as the energy of the incident particle increases since the time integral of the perturbation becomes shorter with increased velocity. At relativistic energies, however, the combined effects of the Lorentz contraction of the field in the direction of motion and certain quantum-mechanical considerations result in an increase of ionization with energy. The treatment given by Bethe, corrected for relativistic effects, gives for the primary ionization in hydrogen,[1]

$$J_p=(2\pi ne^4/mv^2)\cdot(a/I)\times[\log(2mv^2/(1-\beta^2)I)+b-\beta^2]. \quad (1)$$

Here $n$ is the electron density, $I$ the ionization potential, $a$ and $b$ numerical constants. This expression is plotted in Fig. 4 ($I=13.5$ ev).

The existing experimental data has verified the indicated dependence of *total* ionization,[2] but much of the *primary* ionization work[3–5] has been at variance with the theory. It is possible, indeed, to visualize an energy distribution of the secondary electrons which would yield an increase in *total* ionization for a decrease in *primary* ionization with energy. In fact, in one instance[4] results have been interpreted to indicate this.

The principal methods which have been employed in primary ionization investigations have utilized the cloud chamber[6] and the dependence of the efficiency of a Geiger counter upon the primary ionization of a counted particle.[7] Part I of this paper describes the application of the second method to the determination of the primay ionization in hydrogen by electrons of energies from 0.2–9.0 Mev.

The energy loss of the incident particle due to ionization has also been given by Bethe and by Bloch. Though their results differ slightly, the generally accepted Bethe-Bloch expression for the energy loss per unit path may be written as follows:[8]

$$[-(dE/dx)]_{\text{ion}}=(2\pi ne^4/mv^2)\times[\log(mv^2T/I^2Z^2(1-\beta^2))+1-\beta^2]. \quad (2)$$

Here $T$ is the maximum transferable energy to

* Assisted by the Office of Naval Research.
[1] H. A. Bethe, *Handbuch der Physik* (1933), vol. 24, p. 522.
[2] D. R. Corson and R. B. Brode, Phys. Rev. **53**, 773 (1938); W. E. Hazen, Phys. Rev. **67**, 269 (1945).
[3] P. Kunze, Zeits. f. Physik **83**, 1 (1933).
[4] M. G. E. Cosyns, Nature **139**, 802 (1937).
[5] W. E. Hazen, Phys. Rev. **63**, 107 (1943).
[6] E. J. Williams and F. R. Terroux, Proc. Roy. Soc. **126**, 289 (1930).
[7] W. E. Danforth and W. E. Ramsey, Phys. Rev. **49**, 854 (1936).
[8] W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, London, 1936) p. 218.

an electron in a collision as computed by Bhabha.[9] Recently, however, Halpern and Hall[10] have carried out an investigation in which the polarization properties of the medium traversed are considered. The possibility that polarization of the medium might lead to a reduction in energy loss due to a screening effect was first suggested by Swann[11] and treated quantitatively by Fermi.[12] The subsequent investigation of Halpern and Hall yields a variation of ionization loss with energy of the ionizing particle which departs appreciably from the Bethe-Bloch calculation. It is the purpose of Part II to investigate the validity of these results by comparison of the relative stopping powers of carbon and $H_2O$ at various electron energies. Previous attempts at verification have been successful in one case,[13] inconclusive in another.[14] In hydrogen the reduction in loss due to polarization does not appear at energies below about 100 Mev and, consequently, is of no importance in the primary ionization measurements of Part I.

## PART I

### Experiment

The method employed in the determination of the primary ionization in hydrogen utilizes the dependence of the efficiency of a Geiger counter upon the primary ionization. This dependence is as follows:

$$\text{Eff.} = 1 - e^{-lJp}. \tag{3}$$

Hence the counting rate for $N_0$ particles per minute traversing the counter is

$$N = N_0(1 - e^{-lJp}). \tag{4}$$

Here $l$ represents the path length through the counter, $J$ the primary ionization, $p$ the counter pressure in atmospheres. Selection of electron energy ranges was accomplished in two ways.

In the range 0.2–0.75 Mev a magnetic focusing beta-ray spectrometer was employed, following the method of Graf[15] (Fig. 1A). Using various pressures of pure hydrogen in the counter at the collector slit, the counting rate was determined for various energies selected by the magnetic spectrometer. The counter was a thin-wall (0.03 g/cm$^2$) type, the cathode being a coating of Aquadag on the inner surface of the glass envelop. The use of a Neher-Harper quenching circuit and a 64-scalar made possible counting rates high enough to minimize sufficiently the background effects. This data gave a family of curves showing *counts per minute vs. energy* with counter pressure as a parameter. For any energy it was then possible to plot *counts per minute vs. pressure*. The appropriate choice of $lJ$ would then fit expression (4) to each curve, thus determining *$lJ$ vs. energy*. The specification of the path length necessary to determine $J$ was accomplished by normalization with the data at higher energies as discussed below.

For energies exceeding 0.75 Mev the beta-ray spectrometer available was unsuitable, and a coincidence counter method was used. The procedure has been previously described.[16] A fourfold coincidence train of thin-wall counters was employed (Fig. 1B), counters 1, 2, and 4 being filled with an argon-ether mixture at 7 cm Hg, which yielded an efficiency for all particles of very nearly 100 percent, counter 3 containing a pure hydrogen filling at 7 cm Hg. The ratio of

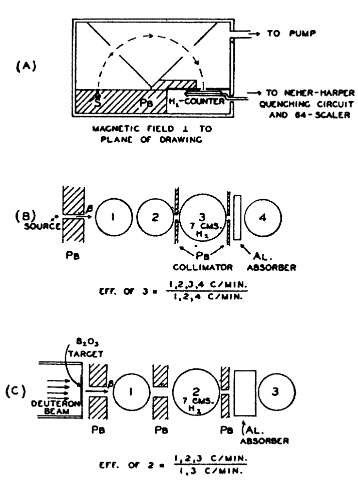


FIG. 1. (A) The beta-ray spectrometer for determination of the primary ionization in the 0.2–0.75 Mev range. (B) The coincidence apparatus for measurements at higher energies. (C) Revised coincidence arrangement using $B^{12}$ beta-spectrum produced by deuteron bombardment of $B^{11}$.

[9] H. J. Bhabha, Proc. Soc. **164**, 257 (1937).
[10] O. Halpern and H. Hall, Phys. Rev. **57**, 459 (1940); **73**, 477 (1948).
[11] W. F. G. Swann, J. Frank. Inst. **226**, 598 (1938).
[12] E. Fermi, Phys. Rev. **57**, 485 (1940).
[13] H. R. Crane, N. L. Oleson, and K. T. Chao, Phys. Rev. **57**, 664 (1940).
[14] E. Hayward, Phys. Rev. **72**, 937 (1947).
[15] T. Graf, J. de phys. et rad. (Ser. 7) **10**, 513 (1939).
[16] F. L. Hereford, Phys. Rev. **72**, 982 (1947).

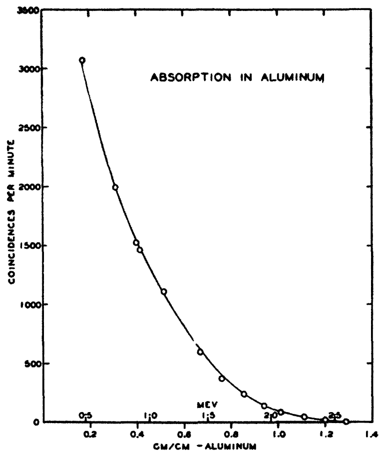


FIG. 2. Absorption in aluminum of beta-rays from the radium source.

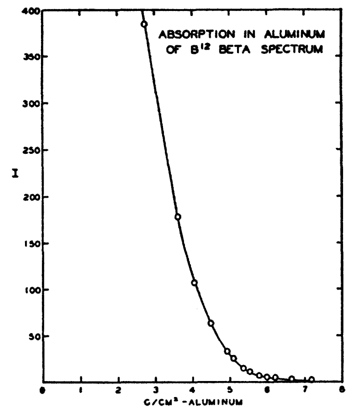


FIG. 3. Absorption in aluminum of beta-rays from $B_{12}$. See Fig. 7 for end-point determination.

coincidences 1, 2, 3, 4 to coincidences 1, 2, 4 clearly gives the efficiency of counter 3. The path length through this counter was limited to a small region about the diameter by a collimator as shown. Knowledge of the efficiency, counter pressure, and path length then allowed computation by (3) of the primary ionization, $J$, for any energy distribution of electrons penetrating all counters. Insertion of various thicknesses of aluminum between counters 3 and 4 made possible determination of $J$ for all electrons of energy in excess of that required to penetrate the absorber, counter walls included.

Using first a radium source, $J$ was evaluated for electron energies in the 0.9–2.5 Mev range. The energy spectrum of the source is indicated by the absorption curve in aluminum (Fig. 2), where the end point was determined by the Feather absorption law.[17] The value of $l$ in the beta-ray spectrometer data was then chosen so as to match values of $J$ as determined from the spectrometer and coincidence methods at about 0.8 Mev. For the evaluation of $J$ at higher energies the beta-spectrum of $B^{12}$ was employed. The deuteron beam of the Bartol Van de Graaff generator focused on a $B_2O_3$ target yielded $B^{12}$ through the $B^{11}(dp)B^{12}$ reaction. The $B^{12}$ spectrum which has an end point at approximately 13 Mev is indicated in Fig. 3.

The short half-life of $B^{12}$ (0.02 sec.) necessitated continuous operation of the generator; the difficulties of prolonged operation made necessary the use of higher counting rates than were previously used. In order to achieve this without loss of genuine counts the hydrogen counter was quenched by a Neher-Harper circuit. Coincidences were recorded by means of the circuit used by Mandeville and Scherb,[18] with which a resolving time of $1.8\times10^{-7}$ second was attained. The consequent low accidental coincidence rate allowed removal of the first counter. Thus the efficiency was determined and primary ionization computed in this case from the ratio of the threefold to twofold coincidences (Fig. 1C).

## Results

The collected data for the primary ionization in hydrogen in the energy range 0.2–9.0 Mev are given in Fig. 4 with the theoretical curve of the Bethe-Bloch theory. The ordinate shows the values of $E/mc^2$ in order that the average value of $J$ for the ionizing component of sea level cosmic radiation can also be indicated. The average value of $E/mc^2$ in this case is taken to be 20, corresponding to the average energy of the meson component at sea level. The unpublished results of an independent experiment conducted in this laboratory by Mr. Alden Stevenson have shown the primary ionization of the meson component and of the total ionizing component at sea level to be essentially equal. It may be pointed out that the value of $J$ for sea level

[17] N. Feather, Proc. Camb. Phil. Soc. **34**, 599 (1938).

[18] C. E. Mandeville and M. V. Scherb, Phys. Rev. **73**, 90 (1948).

cosmic radiation relative to the minimum ionization (1-Mev electrons) is the same as that previously found[16] in a self-quenching helium-butane counter mixture. Figure 4 also indicates the results of several other experimental investigations for the sake of comparison. The high value of $J$ at the minimum obtained by Cosyns is probably due to an underestimation of scattering effects.

## PART II

### Experiment

As previously stated Halpern and Hall show that polarization considerations reduce the ionization loss of a fast charged particle traversing a medium. The effect, which is most prominent in condensed substances, yields a 7 percent reduction in the loss of 1-Mev electrons in carbon while in $H_2O$ it becomes appreciable only at higher energies (Fig. 5). Such a reduction alters the relative stopping powers of the two media, which effect should be observable by means of an absorption method.

We have employed[19] a simple scheme in which the reduction in the coincidence rate of a twofold coincidence train was observed upon the insertion of varying thicknesses of carbon and $H_2O$ (Fig. 6). The outstanding difficulty of the method is that a portion of the apparent absorption is due to the scattering of particles out of the solid angle subtended by the second counter. It is possible, however, to choose sample thicknesses

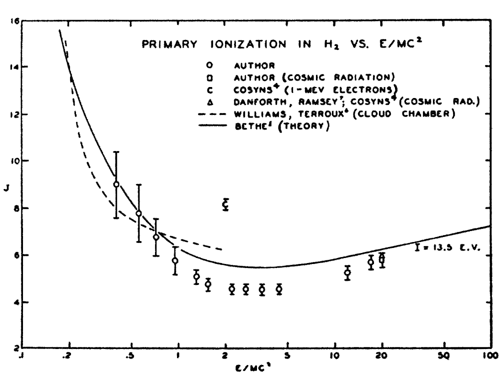


FIG. 4. Results of determinations of the primary ionization, $J$, in hydrogen. The experimental points may be compared with the curve computed from Bethe's theory.

[19] The details of the procedure have been described and some of these results given previously, F. L. Hereford, Phys. Rev. **73**, 1123 (1948).

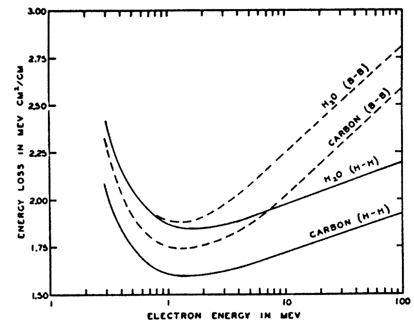


FIG. 5. The theoretical ionization loss for electrons in carbon and $H_2O$. The Halpern-Hall loss is shown by the solid lines, the Bethe-Bloch loss by the dotted lines.

in such a manner that scattering effects are eliminated.

It is well known that for the case of multiple scattering,[20] if the thickness of a layer is given in "radiation lengths," then the mean square angle of scattering of a monoenergetic beam of particles is independent of the atomic number.[21] Consequently, equal thicknesses of two substances so measured should scatter equivalently a monoenergetic beam. However, in the application here we are concerned with a continuous energy distribution. Hence, if our samples are to exhibit equal scattering effects, in addition to being of equal thicknesses in radiation lengths they must have equal stopping powers, for then the scattering loss will form the same percentage of the apparent absorption in each sample. This condition will exist if, for instance, in the case of carbon and $H_2O$,

$$S_{H_2O}/S_C = X_C/X_{H_2O},$$

where $S$ and $X$ are, respectively, the stopping

TABLE I.

| Thickness of samples: Radiation length | $H_2O$ g/cm² | Carbon g/cm | Mean energy Mev | Stopping power ratio: $S_{H_2O}/S_C$ Exp. | $S_{H_2O}/S_C$ Halpern-Hall | $S_{H_2O}/S_C$ Bethe-Bloch |
|---|---|---|---|---|---|---|
| 0.0055 | 0.25 | 0.29 | 1.6 | 1.16±0.02 | 1.16 | 1.08 |
| 0.0079 | 0.36 | 0.41 | 1.4 | 1.17±0.02 | 1.16 | 1.08 |
| 0.019 | 0.83 | 0.97 | 9.0 | 1.14±0.02 | 1.15 | 1.09 |
| 0.032 | 1.37 | 1.66 | 7.4 | 1.16±0.02 | 1.15 | 1.09 |

[20] Williams has given (E. J. Williams, Proc. Roy. Soc. 169, 531 (1939)) as the criterion for multiple scattering,

$$M = (2\pi n Z^{4/3}/\beta^2)(\hbar/mc)^2 t \gg 1 \quad (t \text{ in cm}).$$

For all cases considered here, $M \geqq 2\times 10^3$.

[21] B. Rossi and K. Greisen, Rev. Mod. Phys. **13**, 262–265 (1940).

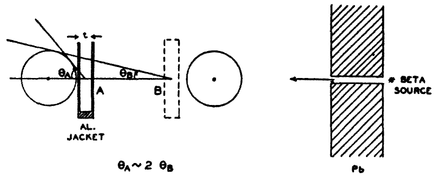


FIG. 6. Schematic diagram of apparatus for investigation of relative stopping powers. $\theta$ represents the maximum angle through which an electron may be scattered and still record a coincidence.

power and the radiation length. Fortunately, in the case of carbon and $H_2O$ this requirement is satisfied to within a few percent if we take the value of $S_{H_2O}/S_C$ given by the Halpern-Hall theory.

The experiment then consists only of the observation of the coincidence rates with equal sample thicknesses (in radiation lengths) of carbon and $H_2O$ inserted alternately into a thin-wall aluminum jacket situated at $A$ as shown in Fig. 6. The equivalence of the rates would indicate verification of the Halpern-Hall value of the stopping power ratio.

In the actual experiment this was very nearly the case. The small differences in the rates, however, were evaluated in terms of stopping power by reference to an aluminum absorption curve, the value of $S_{H_2O}/S_C$ taken as the ratio of $S_{H_2O}/S_{Al}$ and $S_C/S_{Al}$. The procedure was carried through for the electron spectra of both the radium source (Fig. 3) and $B^{12}$ (Fig. 4). In the case of the higher energies of the $B^{12}$ spectrum, the choice of equal sample thicknesses in radiation lengths eliminates confusion between energy loss due to ionization and that due to radiation, the radiation losses being equal. The position of the counters relative to the $B_2O_3$ target was similar to that shown in Fig. 1C. Coincidence rates were determined relative to the deuteron current striking the target in this case.

The equivalence of scattering in the two samples was demonstrated by shifting each sample to position $B$ (Fig. 6) and observing the increased percentage of intensity scattered out of the counter train. The differential scattering probability depends upon the inverse 4th power of the scattering angle; it can be shown in view of this and the geometry employed that the error in the value of $S_{H_2O}/S_C$ due to scattering was at most 0.2 percent.

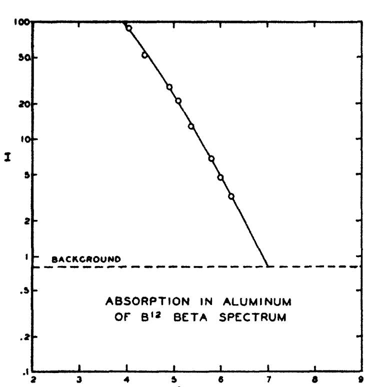


FIG. 7. Logarithmic plot of the higher energy points from Fig. 3 for determination of the end point of the $B^{12}$ beta-spectrum.

## Results

The values of $S_{H_2O}/S_C$ as determined for four effective electron energies are given in Table I with the values predicted by the Bethe-Bloch and Halpern-Hall theories shown for comparison. The experimental results clearly favor the Halpern-Hall calculation.

## Note on Upper Limit of the $B^{12}$ Beta-Spectrum

As a by-product of the investigations at higher electron energies the end point of the beta-ray spectrum of $B^{12}$ was determined by an absorption method. Figure 7 shows a logarithmic plot of the high energy end of the aluminum absorption curve (Fig. 4). The extrapolated curve is seen to cross the background line at 7.0 g/cm². The background was due to accidental coincidences and coincidences from cascade emission of gammas.

In accordance with a modification of the Feather absorption law given by Glendenin and Coryell[22] a value of $E_{max}$ of 13.3 Mev is indicated. This evaluation assumes the validity of the absorption relation at energies in excess of the range where experimental confirmation exists. This is not too unreasonable since the radiation loss in aluminum for these energies is not appreciable; moreover, it generally appears

[22] L. E. Glendenin and C. D. Coryell, Plutonium Project Record 9B, 2.12 (1946).

as large energy losses by a few particles rather than small losses by many.

The upper limit determined from the cloud chamber data of Bayley and Crane[23] by inspection and by Fermi and $K$-$U$ extrapolations are given below for comparison.

| | |
|---|---|
| Inspection............... | $12.0 \pm 0.6$ Mev, |
| Fermi Plot............... | $12.4 \pm 0.6$, |
| $K$-$U$ Plot................ | $14.5 \pm 0.7$, |
| Above value.............. | $13.3 \pm 0.5$. |

[23] D. S. Bayley and H. R. Crane, Phys. Rev. **52**, 604 (1937).

**ACKNOWLEDGMENTS**

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# Shower Production by Penetrating Particles at 14,000 Feet

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Showers produced by penetrating particles were studied at 14,000 feet by simultaneous observations with G.M. counters, a cloud chamber, and an ionization chamber in a combined array. At least two-thirds of the observed showers generated by penetrating particles that struck a five-inch lead absorber consisted of a mixture of energetic electrons and particles heavier than electrons. The frequency of these events at high altitude relative to sea level shows that the initiating particles are not ordinary mesons. The presence of heavier particles in the electron shower indicates that the showers result from nuclear interactions in which the nucleus is disrupted rather than from a simple radiation process. Details of the events and their relation to some other cosmic-ray phenomena are discussed.

## 1. INTRODUCTION

THE production of high energy showers by penetrating particles has been observed with ionization chambers,[1] with cloud chambers,[2] and with counter arrangements.[2]

The observations described in this paper were undertaken in order to study the nature of the showers that have been observed at high altitude under lead shields thick enough to exclude electron or photon initiated showers.[1] For this purpose, the lead was divided into a thick lead shield that was placed above a cloud chamber and a series of lead plates that were placed inside the cloud chamber. A coincident signal from G.M. counters and an ionization chamber controlled the expansion of the cloud chamber. With suitable geometry, this procedure makes possible a detailed study in the cloud chamber of the event responsible for the burst in the ion chamber.[3] Thus it was hoped that the results would provide general information about high energy showers and conclusive evidence as to the nature of the showers studied by Bridge, Rossi and Williams with shielded ionization chambers at high altitudes.[1]

Since the terminology used to describe events

* Now at University of Michigan, Ann Arbor, Michigan. Some of the cloud chamber equipment was constructed during the tenure of a John Simon Guggenheim Memorial Fellowship.

[1] H. Bridge, B. Rossi, and R. Williams, Phys. Rev. **72**, 257 (1947).

[2] See W. B. Fretter, Phys. Rev. **73**, 41 (1948) for cloud-chamber observations and references to previous work.

[3] A brief report of the results was included in a letter by H. Bridge, W. Hazen, and B. Rossi, Phys. Rev. **73**, 179 (1948).