# Direct Comparison of the Penetration of Solids and Liquids by Positrons and Electrons*

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A new experimental technique has been used to investigate the penetration of 1.88-MeV positrons and 1.77-MeV electrons in carbon, aluminum, copper, tin, lead, brass, Teflon, Plaskon, Lumarth, water, benzene, and toluene. These are the first such measurements for liquids. The results, which measure transmissions down to 2%, indicate greater transmission of positrons than electrons in solids and liquids, except in brass and Plaskon. The difference in transmission is 12% for Al, 35% for Pb, and 88% for toluene. The greater transmissions in aluminum and lead are in qualitative agreement with the scattering theory; however, there is at present no theoretical explanation for the measured differences in the rest of the solids and the liquids.

## INTRODUCTION

SOMEWHAT surprisingly, the penetration of positrons through solids and liquids and their corresponding differences from electrons have been subject to very little investigation, either experimental or theoretical. By inserting the appropriate sign in Mott's[1] formula, Fowler and Oppenheimer[2] concluded that the scattering cross section should be different for positrons and electrons. Encouraged by the theoretical prediction, Fowler and Oppenheimer were the first to attempt to show the difference by an experiment. They tried to detect this difference in a cloud chamber. Unfortunately, their cloud-chamber statistics were poor and the effect was not demonstrated conclusively. Later Chang, Cook, and Primkoff[3] failed to observe any significant difference. Lasich was the first one to observe excess of scattered electrons over positrons in single scattering in a number of scatterers, and this was confirmed by Lipkin and White.[4] Later, Seliger[5,6] reported a difference in transmission for positrons and electrons depending upon the energy and the atomic number of the absorber. Rohrlich and Carlson[7] have calculated the energy loss and multiple scattering of positrons and electrons in Al and Pb.

The purpose of the present experimental investigations is to determine the actual differences between 1.88-MeV positrons and 1.77-MeV electrons in their penetration of solids and liquids and to attempt to relate the experimental results to the theory available. A new technique has been developed for the detection of the transmitted beam of positrons, which eliminates the problem of the $\gamma$-ray background associated with the beam of positrons. By this means it was possible to detect a transmitted intensity as low as 2%.

* A preliminary account of some of these results has appeared in: P. S. Takhar, Phys. Can. **22**, 39 (1966); Bull. Am. Phys. Soc. **11**, 467 (1966); Phys. Letters **23**, 219 (1966).

[1] N. F. Mott, Proc. Roy. Soc. (London) **A124**, 425 (1929).
[2] W. A. Fowler and J. Oppenheimer, Phys. Rev. **54**, 320 (1938).
[3] C. H. Chang, C. S. Cook, and H. Primakoff, Phys. Rev. **90**, 544 (1953).
[4] H. J. Lipkin and M. G. White, Phys. Rev. **79**, 892 (1950).
[5] H. H. Seliger, Phys. Rev. **88**, 408 (1952).
[6] H. H. Seliger, Phys. Rev. **100**, 1029 (1955).
[7] F. Rohrlich and B. C. Carlson, Phys. Rev. **93**, 38 (1954).

## EXPERIMENTAL TECHNIQUE AND RESULTS

### A. Penetration of Positrons

Earlier, Seliger[5] and Gubernator[8] used 90° magnetic analyzers to eliminate the $\gamma$-ray background from a radioactive source in measurements of the absorption of positrons. However, in their arrangement there are additional $\gamma$ rays created by annihilation of positrons in the slit, walls, and absorber itself, which cannot be eliminated easily. Thus there is a strong possibility that some $\gamma$ rays always reach the detector in spite of direct shielding. Secondly, the absorber in front of the detector in the presence of a $\gamma$-ray acts as a radiator. This background varies with the thickness of the absorber and with the atomic number $Z$ of the absorber used. Thus in addition to positrons, there may be some knock-on electrons going to the detector. Since this type of detector, viz., ionization chamber, does not distinguish between a positron and an electron it may not be a very suitable method of detecting the transmitted beam.

In the present technique the problem of associated $\gamma$ rays and electrons has been eliminated altogether using a slow and fast coincidence system,[9] thus extending these observations to lower transmissions because of the lower background for positrons. Also a new, precise experimental technique was used to obtain the beam of positrons. By this means it was possible to keep the statistical fluctuations to a minimum.

The positron source used in the present work is $Ge\text{-}Ga^{68}$ (supplied by New England Nuclear Corporation, Boston, Massachusetts), which has a half-life of 280 days and emits a spectrum of positrons with a maximum energy of 1.88 MeV. This particular source is best for investigating the penetration of positrons in solids because of the higher energy and hence larger path length in mm. The size of the source is a 3 mm spot on a $\frac{3}{4}$ in. mount. The method of preparation involves transferring $Ge^{68}$ coprecipitated with $As_2S_3$ to the plastic disc backing and then covering it with aluminized Mylar

[8] K. Gubernator, Z. Physik **152**, 183 (1958).
[9] J. H. Green and G. J. Celitans, Proc. Phys. Soc. (London) **82**, 1002 (1963).

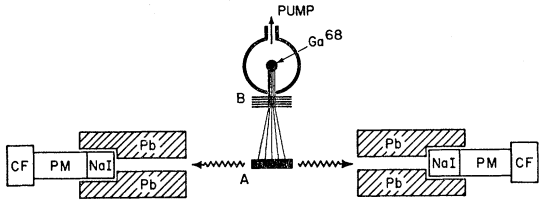


FIG. 1. Source and geometry for positron detection. PM, photomultiplier; CF, cathode follower.

0.00025 in. thick. The strength of the source was 0.1 mCi. The source was mounted at the center of a hollow steel sphere 4 in. in diameter (See Fig. 1.) The positron beam was obtained through a steel exit port 0.4 in. in diam and 0.0006 in. in thickness. The pressure inside the sphere was maintained at $10^{-5}$ Torr throughout the observations. The absorbers of varying thickness were introduced against the window and the transmitted beam allowed to annihilate in an aluminum slab. The annihilation photons were detected by $2\times1\frac{3}{4}$-in. NaI crystals supplied by Harshaw Chemical Co. Each crystal was coupled to a Dumont 6292, which is a 2-in. fourteen-stage photomultiplier. Heavy lead shielding of the order of 3 in. was used to shield the crystals from any direct radiation. The positron source and geometry are shown in Fig. 1, where *A* is the aluminum block and *B* are absorbers. Two photomultipliers were kept about 14 in. away from the annihilation aluminum which was in the path of the positron beam, and annihilation $\gamma$-rays were detected under narrow geometry. The pulses from the two detectors are amplified and shaped by limiters and then mixed in a 6BN6 to give a coincidence count. This is a modified version of the circuit of Fischer and Marshall.[9–11] The output of the 6BN6 is amplified and fed to the discriminator. Similarly, single pulses from the detectors were amplified and fed to the single-channel pulse-height analyzers. The outputs of the three discriminators are combined in a triple-coincidence circuit to give the final count rate. The count rate from the annihilation material was about 800 counts/20 min for zero absorber thickness, with the background count due to chance coincidences and cosmic-ray showers of the order of 5 counts/20 min, which is negligible compared to the beam intensity. Carbon (in the form of pure graphite), aluminum, copper, tin, lead, brass, Lumarth (cellulose acetate), Teflon (polytetrafluoroethylene), Plaskon (melamineformaldehyde), benzene (Fisher's certified ACS sp.gr. 0.879), toluene (Fisher's certified ACS sp. gr. 0.866), and water (distilled) were investigated by the above method. The relative transmission of beam intensity$\times100$ is plotted against the thickness in mg/cm$^2$ for C, Al, Cu, Sn, and Pb in Fig. 2. The plots are nonlinear and do not define ranges of positrons. Plots for other materials follow a more or less similar trend and hence there is no need to show these graphs on a linear plot. The plots are linear on a semilogarithmic plot in the case of metals as shown in Fig. 3 and predict a clear $x$-axis intercept, i.e., relative ranges of positrons in the absorbing materials. Thus the absorption is exponential. However, this is not quite true for brass, carbon, and other compounds at lower transmission as shown in Figs. 3 and 4, where extrapolated ranges could be obtained. Thus positron ranges are

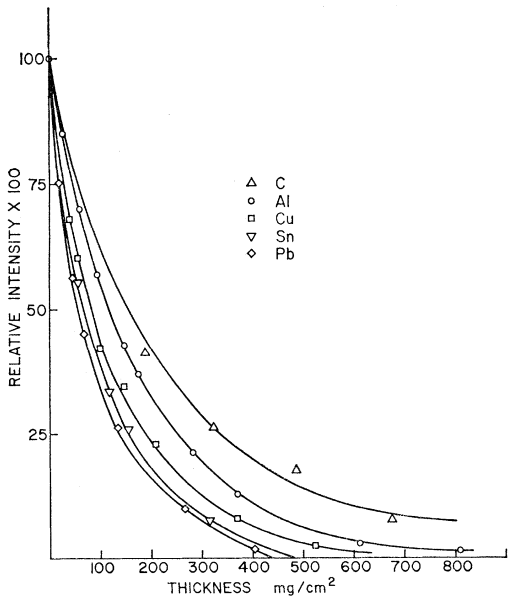


FIG. 2. Linear plot of transmission of positrons in C, Al, Cu, Sn, and Pb.

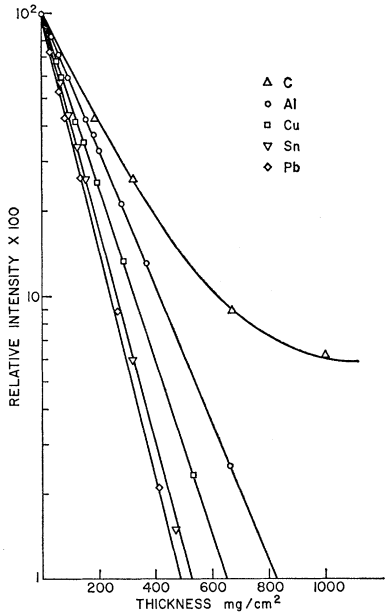


FIG. 3. Semilogarithmic plot of transmission of positrons in C, Al, Cu, Sn, and Pb.

[9] J. Fischer and J. Marshall, Rev. Sci. Instr. **23**, 417 (1952).
[11] R. Green and R. Bell, Nucl. Instr. **3**, 127 (1955).

well defined in solids by this slow and fast coincidence technique which eliminates background effects due to $\gamma$ radiation and electrons.

### B. Penetration of Electrons

Similar experiments have been performed to measure the penetration of electrons through solids and liquids by an analogous technique. The electron source was mounted at the center of the same hollow steel sphere as was used for the positron source and a thin-window Geiger-Müller counter was used for the detection of the electrons. In order to keep the same geometry for both positrons and electrons, the Al block ($A$ in Fig. 1),

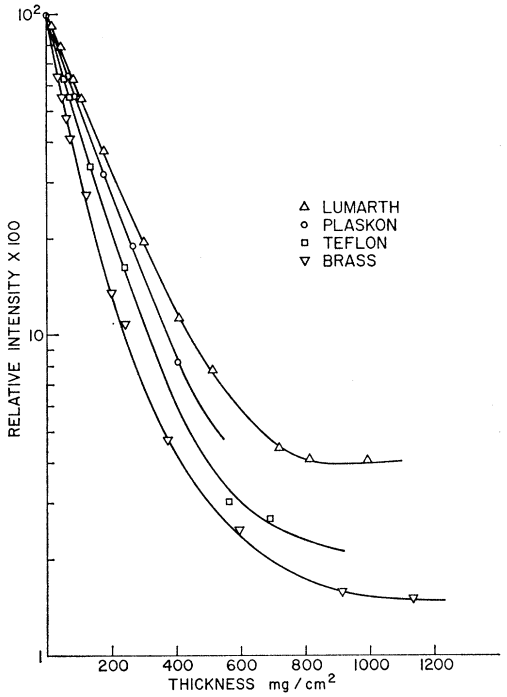


FIG. 4. Semilogarithmic plot of transmission of positrons in Lumarth, Plaskon, Teflon, and brass.

was replaced by the detector window. In this manner quite similar curves have been obtained for electrons using $Rb^{86}$ as an electron source which emits a spectrum of electrons with a maximum energy of 1.77 MeV and has a half-life of 18.7 days. The energy of the electrons is very close to that of positrons from $Ga^{68}$, which emits positrons of maximum energy 1.88 MeV. The electron energy differs from that of positrons only by 6%, which is close enough for comparison. The transmission curves on linear and semilogarithmic plots are very similar to those of positrons after background correction; hence, there is no need to show all of these curves. However, for investigating the comparative transmission of positrons and electrons, a plot of relative transmission versus thickness is shown in Fig. 5 for

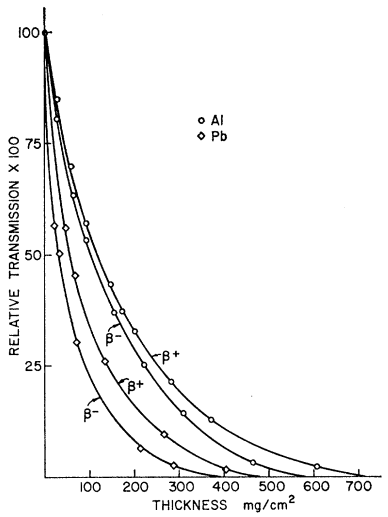


FIG. 5. Comparative transmission of positrons and electrons in Al and Pb.

both positrons and electrons in Al and Pb. The plot clearly indicates greater transmission of positrons than electrons. A similar plot for water and toluene is shown in Fig. 6, which again shows much larger transmission of positrons as compared to electrons for the same thickness. This is also true for Teflon and Lumarth; however, for brass and Plaskon the situation reverses, i.e., a greater number of electrons are transmitted than positrons.

### C. Analysis of Data

The absorption of positrons and electrons is exponential to a good approximation, that is, $N(t)=N_0e^{-\mu t}$, where $N_0$ is the activity without absorber, $N(t)$ is the activity observed through a thickness $t$, and $\mu$ is the

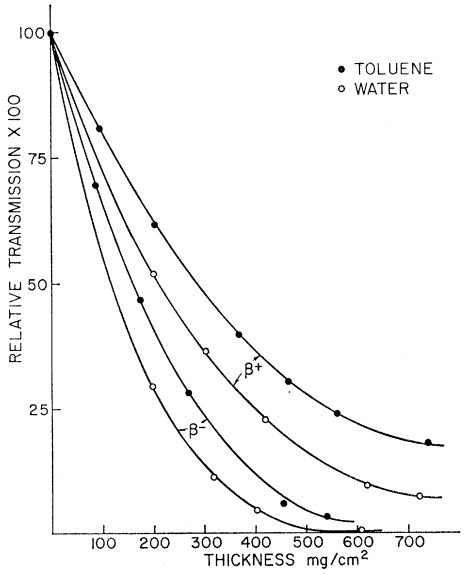


FIG. 6. Comparative transmission of positrons and electrons in water and toluene.

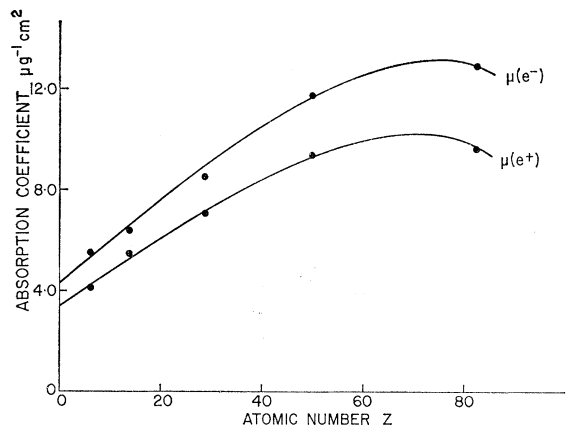


FIG. 7. The absorption coefficient $\mu$ versus atomic number $Z$ for positrons and electrons.

absorption coefficient. Thus the absorption coefficients in different materials can be calculated from the experimental data. In the present work, absorption coefficients for a number of solids and liquids have been calculated by a weighted least-squares fit to the linear part of the experimental data using an IBM 1620 II Computer. Table I shows the absorption coefficients $\mu(e^+)$ for positrons and $\mu(e^-)$ for electrons in $gm^{-1}$ $cm^2$ for C, Al, Cu, Sn, and Pb. The dependence of the absorption coefficients $\mu(e^+)$ and $\mu(e^-)$ upon atomic number $Z$ is shown in Fig. 7. This shows that as $Z$ increases the efficiency of the absorption mechanism increases; however, it may go through a maximum. This possibility is being investigated at present. The absorption coefficient for electrons is greater than that for positrons for each element, showing greater absorption of electrons than positrons. The ratio of the range $r^+$ of positrons to the range $r^-$ of electrons increases with the atomic number $Z$, as given in the Table I. Table II shows the corresponding results for brass, Teflon, Lumarth, and Plaskon. The absorption coefficients for liquids are given in Table III. The difference in absorption is much more pronounced in case of liquids than of solids and will be reported elsewhere. The ratio $r^+/r^-$ is almost 2 for liquids, as shown in the Table III. The experimental errors in the absorption coefficients were about 4 to 7%.

TABLE I. Absorption coefficients in $gm^{-1}$ $cm^2$ and ratios of ranges of positrons and electrons, for elements.

| | Carbon | Aluminum | Copper | Tin | Lead |
|---|---|---|---|---|---|
| $\mu(e^+)$ | 4.25 | 5.65 | 7.15 | 9.39 | 9.53 |
| $\mu(e^-)$ | 5.50 | 6.34 | 8.47 | 11.76 | 12.84 |
| $r^+/r^-$ | 1.29 | 1.12 | 1.19 | 1.29 | 1.35 |

## DISCUSSION

Differences in the scattering behavior of positrons and electrons have been investigated theoretically by Rohrlich and Carlson.[7] They calculated the energy loss and multiple scattering of positrons and electrons in Al and Pb using correct cross sections for elastic and inelastic scattering.

At lower energies positrons lose energy at a faster rate than electrons. This fact, coupled with the fact that for low $Z$ the multiple scattering of electrons is only slightly greater than that of positrons, implies that if the transmission of positrons is ever to be lower than that of electrons, it must occur at low energies and low $Z$. At higher $Z$ the excess multiple scattering of electrons over positrons overshadows the small energy-loss differences. Therefore, at higher energies even for materials of low $Z$, positrons should be transmitted to a greater extent than electrons. This is what actually was found in the present experiments for C, Al, Cu, Sn, Pb, and a number of other materials, where positrons are transmitted to a greater extent than electrons under similar geometrical conditions. However, in order to compare experimental results with theory, one must consider the problem of multiple scattering. The exact cross section for the elastic scattering of electrons and positrons by the Coulomb field of a charge $Ze$ was given by Mott in the form of a series in Legendre polynomials. The second-order Born approximation of this cross section for positrons and electrons is given[12,13] by

$$\sigma(\theta, s)_\pm = (d\sigma^\pm/d\Omega) = (e^2Z/2\beta^2E)^2[1/\sin^4(\tfrac{1}{2}\theta)] \times [1-\beta^2\sin^2(\tfrac{1}{2}\theta) \mp (Z/137)\sin\tfrac{1}{2}\theta(1-\sin\tfrac{1}{2}\theta)], \quad (1)$$

where the upper sign is for positrons and lower for electrons, $E$ is the total energy, $Z$ is the atomic number, $e$ is the electron charge, $s$ is path length, $\theta$ is the angle of scattering, and $\beta$ is the ratio of particle velocity to the velocity of light. This applies for light elements; however, for heavier elements one must resort to a

TABLE II. Absorptions coefficients in $gm^{-1}$ $cm^2$ and ratios of ranges of positrons and electrons, for other solids.

| | Brass | Teflon | Plaskon | Lumarth |
|---|---|---|---|---|
| $\mu(e^+)$ | 9.16 | 6.73 | 5.83 | 5.15 |
| $\mu(e^-)$ | 8.27 | 7.54 | 5.72 | 6.05 |
| $r^+/r^-$ | 0.90 | 1.12 | 0.98 | 1.17 |

[12] W. H. McKinley and H. Feshbach, Phys. Rev. **74**, 1759 (1948).
[13] E. Segre, *Experimental Nuclear Physics* (John Wiley & Sons, Inc., New York, 1953), Vol. 1, p. 252.

numerical summation of the Mott solution. This calculation was done at various energies, by Barlett and Watson[14] for electrons and by Massey[15] for positrons. In order to estimate the positron-electron differences in multiple scattering, Rohrlich and Carlson[7] calculated the average penetration depth at which the original direction of the particle beam is essentially lost. They assumed that the longitudinal distribution is determined by Legendre's polynomial $\langle z^n P_l, (\cos\theta)\rangle_{\text{av}}$ for all $n$ and $l$. They defined the average total energy at which particles have essentially lost their initial orientation by the condition $\langle\cos\theta\rangle_{\text{av}}=1/e$, where $e$ is the base of natural logarithms, and hence the distance of penetration $z_d$ is given by

$$2\pi N\int_0^{z_d} ds\int_{-1}^{1}\sigma(\theta, s)\,(1-\cos\theta)\,d\cos\theta=1, \qquad (2)$$

where $s$ is the path length, $\sigma(\theta, s)$ is the Born approximation of the scattering cross section given by (1), and $N$ is the number of atoms per unit volume present in the material. According to Rohrlich and Carlson,[7] $z_d$ represents the ability of a particle to penetrate. They calculated the ratio $z_d^+/z_d^-$ in Al and Pb in the low-energy range. The theoretical ratio of $z_d^+/z_d^-$ is compared with the experimental ratio $r^+/r^-$ in Table IV. The experimental and theoretical ratio of $r^+/r^-$ is always greater than unity for Al, Cu, Sn, and Pb. This shows that a larger percentage of positrons are transmitted than electrons as predicted by theory. According to theory, the difference between $r^+$ and $r^-$ is about 6% for Al and 40% for Pb. The present experiment yielded 12% for Al and 35% for Pb. The present theory does not take account of possible straggling effects. However, there is qualitative and quantitative agreement between the theory and the experiment within the experimental error which is 4 to 7%.

TABLE III. Absorption coefficients in $\text{gm}^{-1}$ $\text{cm}^2$ and ratios of ranges of positrons and electrons, for liquids.

| | Water | Toluene | Benzene |
|---|---|---|---|
| $\mu(e^+)$ | 3.72 | 2.63 | 2.80 |
| $\mu(e^-)$ | 6.60 | 4.78 | 4.83 |
| $r^+/r^-$ | 1.78 | 1.88 | 1.72 |

[14] J. H. Bartlett and T. A. Watson, Phys. Rev. **56**, 612 (1939).
[15] H. S. W. Massey, Proc. Roy. Soc. (London) **A181**, 14 (1942).

TABLE IV. Comparison of positron and electron ranges.

| | Al | Cu | Sn | Pb |
|---|---|---|---|---|
| Experiment $r^+/r^-$ | 1.12 | 1.19 | 1.25 | 1.35 |
| Theory[a] $z_d^+/z_d^-$ | 1.06 | ••• | ••• | 1.40 |

[a] Reference 7.

In fact, the statistical fluctuations in the energy loss are relatively more important at lower energies, i.e., less than 1 MeV. In the present experiment the energy of electrons or positrons used is of the order of 2 MeV and thus the straggling effects should be small enough to be ignored.

## CONCLUSIONS

The new technique which reduces the background for pesitrons has been quite useful in extending the observations to lower transmission and enables us to measure the differences in transmission of positrons and electrons. The present experimental results indicate that positrons are transmitted in larger percentages than electrons for C, Al, Cu, Sn, Pb, and a number of other materials. There are few exceptions, such as brass and Plaskon. In the case of elements, as shown in Fig. 7, the difference in transmission increases as atomic number $Z$ increases. The present results do not agree with the measurements of Chang, Cook, and Primakoff,[3] who did not observe any significant difference in transmission between positrons and electrons in the case of Al. The results for Al are in agreement with those of Seliger,[6] who observed greater transmission for positrons at 960 keV.

At present there is no theoretical explanation or calculations for the much larger difference reported here for the case of liquids. The difference for toluene is 88% as compared to lead, in which case the positron-electron difference in penetration is 35%. Attempts should be made to explain these results.

## ACKNOWLEDGMENTS

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