CHAPTER I

1. Status

1.1 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.

The information about the energy loss and the ranges of electrons and positrons in different materials is frequently required for several applications in nuclear engineering, nuclear physics, health physics, semiconductor detector physics and many other related fields. The study of the passage of electrons and positrons through matter is also of fundamental interest to promote the complete understanding of their interaction mechanism with matter.

The germinal idea for this work came into being with the calculations by Mott of the cross section for elastic single scattering of electrons by nuclei, using the Dirac wave equation for the electron. He was able to show that probability that an electron will be scattered into an element of solid angle dΩ at an angle θ to the
original direction is given\(^1\) by

\[ I(\theta) d\Omega = N(t\frac{e^2}{2M^2c^2}(1-\beta^2)\cos \theta \sec \frac{1}{2} \theta f(\theta, \beta, Z) d\Omega \] \hspace{1cm} (1.1)

Here \( N \) is the number of atoms per unit volume, \( t \) is the thickness, \( Z \) is the atomic number, \( e \) and \( m \) are the charge and rest mass of the electron respectively and \( \beta \) is the ratio of the particle velocity to the velocity of light.

The function \( f(\theta, \beta, Z) \) is a convergent infinite series and arises due to the application of the relativistic Dirac theory of the electron to the nuclear scattering problem, using the Born approximation. The function \( f(\theta, \beta, Z) \) is given as

\[ f_{\text{Mott}} = 1 - \beta^2 \sin^2 \frac{1}{2} \theta \pm \frac{1}{2} \frac{1}{2} \pi Z^2 \beta (1 - \sin \frac{1}{2} \theta) \sin \theta / 2 \] \hspace{1cm} (1.2)

where \( \lambda = \frac{\hbar}{\mu c} = 1/137 \)

By inserting the appropriate sign of charge in Mott's formula, Fowler and Oppenheimer\(^2\) (1938) 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 detect the difference by an experiment. They tried to detect this difference in a cloud chamber, however their cloud chamber statistics were poor and the effect was not demonstrated conclusively.

For some time after the appearance of Mott's \(^1\) derivation, both theoretical and experimental work centered about the verification of the scattering formula itself and particularly of the so-called "Mott formula" for low Z.

Lasich\(^3\) was the first one to observe an excess of scattered electrons over positrons in single scattering in a number of scatterers. Lipkin and White\(^4\) also confirmed an excess of scattered electrons over positrons in a number of target materials. Chang, Cook and Prinkoff\(^5\) failed to observe any significant difference in transmission between positrons and electrons in the case of Al.

It is now a well-established fact that electrons or positrons on passage through matter, undergo both elastic as well as inelastic collisions with the orbital
electrons of the interacting atoms and by radiative collisions with nuclei and electrons. Also, they get scattered either by a single collision in the Coulomb field of a nucleus or by a large number of small deviations. Both kinds of interactions have been studied extensively. The elastic as well as the inelastic scattering cross-sections of electrons differ from that of the positrons by a few percent. Therefore, it is interesting to investigate the total stopping power, the multiple scattering and the ranges of these particles in the media they traverse.

The range of the electrons is purely an experimental concept. Several definitions have been employed to obtain the ranges from the transmission curves. According to Varder, one extrapolates the linear portion of the absorption curve of monoenergetic electrons to the thickness axis to obtain the so-called practical maximum range, $R_p$. Some workers have defined the maximum range $R_p$ as the thickness corresponding to the point where the tail of the transmission curve itself meets the background level.
Further, with the development of linear accelerators, workers like Hereford and Swann measured the absorption of monoenergetic electrons of a few MeV. A comprehensive summary of the experimentally obtained ranges of 59 monoenergetic electron energies and 35 continuous beta-ray energies has been reviewed by Katz and Penfold. They have pointed out that there is no discernible difference between the ranges of monoenergetic electrons of energy $E$ and the continuous energy electrons of end point energy $E_{\text{max}} = E$.

The measurements of the ranges of positrons were sufficiently delayed due to some practical difficulties, such as:

1. Detection of positrons.
2. Non-availability of suitable positron sources.
3. The difficulty of getting a collimated beam of positrons without any background radiation. The ranges of positrons of energy below one MeV were first reported by Seliger in 1955. Gubemator (1958) performed the measurements of positrons and
electrons ranges of very low energy (up to 160 KeV) in aluminum, and a few other metals. He developed the corresponding range-energy relations empirically.

As discussed by Segre, the theoretical range of electrons is defined as the limiting thickness of the foil, beyond which essentially none of the originally incident electrons emerges out. Such a thickness does not exist practically owing to the straggling problem. Thus, in spite of the availability of the theories concerning the slowing down processes and multiple scattering, it has not been possible so far to obtain a theoretical range with which to compare the ranges extracted from the experimental transmission curves. Recently Batra and Sehgal has reported a new method for calculating the ratio of the straggling free ranges $R^+/R^-$. They have done calculations for carbon, aluminum, copper, silver, tin, gold, lead and some liquids. Their calculated ratio of ranges $R^+/R^-$ for positrons and electrons agrees fairly well with the present measurements. However, their calculations do not agree with the present measurements for rare earth foils.
The purpose of the present experimental investigation was to determine the actual differences between positrons and 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 positrons. This results in a precise and accurate determination of the ranges of positron. Also some work on evaluation of scintillation counters and statistics of photomultipliers is also reported in the present thesis.

1.2 SUMMARY OF THE PAST EXPERIMENTAL APPROACHES

An adequate experimental data concerning the ranges of monoenergetic electrons and that of continuous beta-spectra in different materials, particularly in aluminum, are available in the literature.10-12 A few measurements of positron beam attenuation by foils have also been reported.

The general experimental observation is that the transmitted intensity of mono-energetic electrons after passing through foils, first decreases slowly
with increasing thickness, then decreases exponentially over an appreciable range of thickness, and at the end enters into the background intensity. For instance, Marshall and Ward's experiment on the absorption of monoenergetic electrons of energies: 420KeV to 1696KeV in aluminum, illustrates the nature of the electron transmission.

The measurements due to Eddy and Gleason et al. have proved that in the case of the absorption of beta-rays, the geometry of the experimental arrangement plays an important role. That is why the various empirical range energy relations based on experimental ranges possess deviations from one another. Gleason et al. gave an improved version of beta counting at defined geometries. They placed a thick brass plate collimator very close to the window of a G.M. Counter. The collimator possesses a hole coaxial with the anode wire of the counter and is somewhat smaller than the window, thus fixing the geometry of the counting set-up.

It is worthwhile to discuss briefly the characteristic features such as the definition of the
range employed, the geometry of an experimental
set-up, the effect of the position of the foils in
some of the measurements made on the transmission of
positrons and electrons.

A. Hereford and Swann's Experiment:

In 1950 Hereford and Swann measured the ranges
of mono-energetic electrons of energies lying between
3.0 to 12.0 MeV in aluminum, and copper. They studied
the absorption of these electrons and from their
absorption curves, they obtained the practical ranges
$R_p$ i.e. by extending the linear portion to the back­
ground level. The main feature of their results is
that the absorption curves for different energies have
the same shape. Even the tail portion of these curves
are identical indicating the state of complete diffusion
near the end of the electron range. This observation
makes the extrapolation procedure for obtaining $R_p$
more justified. They estimated the probable error in
measurements to be $\pm 0.1 \text{ gm/cm}^2$. They also demonstrated
semi-empirically the effect of multiple scattering on
the range.
The values of $R_p$ obtained from this experiment are highly geometry dependent and the authors have not mentioned about the possible influence of the change in geometry of the experimental set-up on $R_p$.

B. Seliger's Experiment:

Seliger\textsuperscript{9,10} has performed a series of experiments to study the back-scattering and transmission of electrons and positrons. In 1955, he measured the transmission of monoenergetic electrons and positrons of various energies (159 keV to 960 keV) in Al, Ag, Sn, Au and Pb foils.

In his experimental set-up, beta-rays of the desired energy were selected from a radio-active source by using a 90-degree magnetic analyser. The collimated beam of these particles is allowed to fall perpendicularly on the face of an absorber which forms the window of a 2 \( \pi \) beta-counter. The counting efficiency of his counter was better than 99\% even for electron energies of few hundred electron volts. His measurements prove that the transmission of positrons is greater than that of the electrons in all cases except at low energy ($\sim$100keV) in aluminum.
Seliger has not evaluated the ranges from his absorption curves for different metals. In his experiment, the relative transmission of positrons of 960 keV in lead and aluminum has been measured only up to 35% and 20% respectively. And, hence the estimation of ranges from these curves does not seem possible. No reason has been assigned why it was not possible to measure with this set-up, the transmission down to few percents. Actually, each positron-emission is followed by a nuclear gamma-transition. Also, there are additional $\gamma$-rays created due to annihilation of positrons in the slit in Seliger's experiment. Thus, the gamma-rays background in his experimental arrangement was probably very large.

C. Gubernator's Experiment

The measurements of the ranges of low energy (below 160 keV) electrons and positrons in aluminum were performed by Gubernator\textsuperscript{12} in 1959. He made use of the magnetic spectrometer to get the desired energy of electrons and positrons. The beam from the magnetic spectrometer impinges on the aluminum foils having
thickness between 0.5 and 100 microns. The transmitted beam of electrons and positrons were detected by a G.M. Counter having a lateral inlet window of 7.4 mm diameter. The distance between the absorption foil and the window was about 5 m.m.; thus the mean solid angle of the absorption foil in the counting tube window is almost $\pi$. The whole system was kept in a vacuum chamber having pressure of $10^{-6}$ torr.

The ranges $R_0$ (maximum ranges) were estimated from the absorption curves by using the definition due to Chalmers. The mean error in each value of the range was estimated to be $\pm 2\%$. The measured ranges were expressed in terms of energy as follows:

$$R^-_0 = 773 \ E^{1.70} \quad (1.3)$$
$$R^+_0 = 759 \ E^{1.72} \quad (1.4)$$

Where $R^+_0$ and $E$ are expressed in milligm/cm$^2$ and MeV respectively. The equations (1.3) and (1.4) deviate by $\pm 0.3\%$ from the measured values.

This experiment concludes that the ranges of positrons in Al are less than those of the electrons in
the energy region from 10 KeV to 160 KeV. These
results are in qualitative agreement with the similar
measurements due to Saliger. Further, the maximum
ranges \( R_0 \) for the energy region considered are, on the
average, about 12% greater than the extrapolated
ranges \( R_0 \) and the values of \( R_0 \) are smaller by about
12% when compared with the true ranges obtained from
collision loss considerations by Nelms. These
differences appear because of the use of different
definitions. In 1959, Gubernator and Flammorfeld measured the ranges of 40-160 KeV electrons and
positrons in Cu, Ag, and Au. They reported that in
copper, the positrons travel less than electrons of the
same energy; while in Ag and Au, they travel more than
electrons. The latter finding disagrees with the
earlier results.

D. Agu, Burdett and Hatukiwa’s Experiments:

These workers have measured the transmission
of electrons of homogenous energy from 0.25 to 0.75 MeV
in Be, Al, Cu, Ag and Au foils by directly measuring the
incident and the transmitted electron currents.
A well-collimated beam of 1 MeV electrons from an electrostatic generator was allowed to fall on the foil clamped at a distance of 0.1 cm above a collecting cup. The solid angle subtended at the centre of the foil by the aperture of the collector was 93\% of 2\pi. The current $i_F$ due to incident electrons on the foil and the transmitted current $i_C$ were recorded simultaneously by independent galvanometers. The current $i_R$ due to electrons reflected back from the collector through the collector aperture was also measured by another galvanometer. All the measurements were recorded at a fixed positive bias of 100 volts. Under these experimental conditions, the reflection coefficient was found to increase with foil thickness, at first linearly from the origin and then approaches a horizontal asymptote at 11\% which is independent of the incident beam energy. The transmission coefficient $i_C/i_F$ was corrected for the reflected electrons.

The transmission curves thus obtained were found to be reproducible to within 2\%. The estimated "extrapolated ranges" from these transmission curves
are shorter by about 6% from those due to earlier investigators.\textsuperscript{7,10} These authors also studied the effect of geometry on the transmission and reported that for poor geometry; the extrapolated ranges are still shorter.

Since it is not explainable why the extrapolated ranges obtained from this experiment are shorter than the earlier measurements; the importance of the experiment lies simply in demonstrating the qualitative nature of electron transmission in metallic foils of various atomic numbers.

E. Patrick and Rupaal's Experiment:

Recently Patrick and Rupaal\textsuperscript{23} reported some work on relative penetration of positrons and electrons in Al, Cu, Sn and Pb. They found the absorption of positrons higher in some materials in 0.320 MeV region and vice versa in other materials. They have chosen a different geometry than other workers. They have used standard coincidence techniques to determine the absorption of positrons and electrons. Their results were Z dependent as expected, however, greater
transmission of electrons than positrons is in disagreement with the prediction of Rohrlich and Carlson.4

F. THONTADYRA AND UMAKANTHA'S EXPERIMENT:

Thontadyra and Umakantha25 have investigated energy dependent absorption of positrons and electrons in Al, Sn and Pb. According to their data, electron-positron differences range from 4 to 10% up to 2 MeV. These findings contradict the theory14 and the experiments reported in this thesis on ranges of positrons and electrons.

1.3 THE STATEMENT OF THE PROBLEM

It is somewhat surprising that in spite of the sufficient existing knowledge of the interaction mechanism of electrons and positrons with matter, least attempts had been made to interpret the measured ranges7 in various materials. Perhaps, this is because of the complex nature of the problem.
The most important aspect of experiments is slow-fast electronics systems and preparation of the radio-active sources. All the electronics required was developed, which includes scintillation counters and preamplifiers and various other accessories needed. Photomultipliers for the scintillation counters were tested. A hollow steel sphere 4 in. in diameter with steel exit port 0.426 diameter and .0006 in. in thickness was developed. The strength of the window was such that a constant vacuum of the order 10⁻¹⁶ Torr. could be maintained. A special attention was paid to the shielding to avoid health hazard.

The absorption of positrons and electrons is exponential to a good approximation, that is

\[ N(t) = N_0 e^{-\mu t} \]

where \( N_0 \) is the activity without absorber, \( N(t) \) is the activity observed through a thickness \( t \) and \( \mu \) is the absorption coefficient. 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 experimental data using an I.B.M. 1620
II Computer. The absorption coefficients \( \mu(e^+) \) for
positrons and \( \mu(e^-) \) for electrons have been measured
for C, Al, Cu, Y, Nd, Ho, Yk, Sn, and Pb. 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 \( R_p^+ \) of positrons to the range \( R_p^- \) of
electrons increases systematically with the atomic
number \( Z \). The absorption coefficients for liquids
were also measured. The difference in absorption is
much more pronounced in case of liquids than of solids.
The data on rare earths such as ytt\( \gamma \)-thium, neodymium,
holinium, ytterbium indicate greater anomalies.

The experimental errors in the calculations
of the absorption coefficients are about 4 to 7
percent. The measured ranges \( R_p^+ \) and \( R_p^- \) were compared
to theoretically predicted ranges.\(^{14,24,30}\)
REFERENCES

6. Varder, R.W. Phil Mag. 29, 725 (1915)
FIG. 24 SEMILOGARITHMIC PLOT OF THE ATOMIC NUMBER $\Sigma Z$ VS. THE RATIO $\frac{R_p}{R_p}$ FOR SOLIDS & LIQUIDS
Figure 23

Linear plot of ratio of ranges $R_p^+/R_p^-$ vs. atomic number $\Sigma Z$ for solids and liquids.