PHYSICAL REVIEW VOLUME 92, NUMBER 2 OCTOBER 15, 1953

Relative Ionization by Cosmic-Ray μ Mesons in a Liquid Scintillator*

R. BASKIN† AND J. R. WINCKLER
University of Minnesota, Minneapolis, Minnesota
(Received January 22, 1953; revised manuscript received June 8, 1953)

Measurements of the rise in energy loss of μ mesons of energy between 385 Mev and 2200 Mev in traversing an xylene solution have been made. The observed pulse-height distribution is compared with the most probable energy loss and median energy loss as found using the Landau theory without a density correction and with a density correction as calculated by Sternheimer. The result of this measurement favors a density correction to the theory of energy loss.

INTRODUCTION

An attempt has been made to measure the increase in energy loss for a μ meson of increasing relativistic velocity in traversing a condensed material.

The theory of energy loss of charged particles in passing through matter was first proposed by Bohr.[1] Later work by Bethe and Bloch[2] using quantum mechanics improved quantitatively the agreement between measured and calculated energy loss. The equation Bethe and Bloch arrived at has come to be known as the Bethe-Bloch formula[3] and represents what is commonly called the mean energy loss. Further calculations on the energy loss of relativistic particles in passing through condensed material have been recently made.[4–7] The influence of the electric polarization of the medium on the electric field of the passing particle reduces the energy loss for incident particles of relativistic velocities. A search for this effect, which is called the density effect, in anthracene, sodium iodide, and silver chloride has recently been reported by Bowen and Roser,[8] Hudson and Hofstadter[9] and Whittemore and Street.[10]

One of the problems in this investigation is to arrive at a satisfactory basis for comparison of the experimental results with theory. The problem arises because the energy loss of a charged particle of unique velocity in passing through matter is not unique, but there is a distribution in energy loss. The form of the distribution depends on the amount of loss in relation to the kinetic energy of the particle. For the case of this experiment, where the loss is very much less than the kinetic energy, the distribution is nonsymmetrical with a high-energy tail. As the loss begins to be appreciable relative to the particles' kinetic energy, the distribution becomes more symmetrical. The form of the distribution function and values for the most probable, mean, and median energy loss of the distribution have been given by Landau[11] and Symon,[12] using the Bethe-Bloch formula in deriving the distribution function. The mean energy loss given by the Bethe-Bloch formula coincides with the most probable energy loss of the fluctuation theory only for the symmetrical type distribution, i.e., when the energy loss is a considerable fraction of the kinetic energy of the particle. The comparisons of the experimental and theoretical values are here carried out, firstly on the basis of the median energy loss of the Landau distribution, which can be obtained by an objective numerical analysis of the data, and secondly by estimating the most probable value of the experimental histograms, which is less objective, but not necessarily less accurate, than the first method. Also calculated for comparison is the mean energy loss of the Bethe-Bloch type, as given recently by Sternheimer.[7]

The development of liquid scintillators and high-gain photomultipliers in the past several years has made possible the determination of the density correction in a condensed material. Liquid scintillators permit the material in which the ionization loss is to be measured to be of large cross-sectional area and thus allow reasonably high counting rates when the particle is a cosmic ray μ meson. In other respects liquid scintillators are generally inferior to good crystal scintillators.

EXPERIMENTAL ARRANGEMENT

The experimental arrangement for this experiment consists of a Geiger counter telescope in which is placed the liquid scintillator. The liquid scintillator was 5 g of *p*-diphenylbenzene, plus 10 mg of diphenylhexatriene per 1000 cc of xylene. The photomultiplier used was RCA 5819 run with photocathode at ground potential, the first two stages at 100 volts and the remaining stages at 50 volts. The energy of the μ meson whose pulse height is measured is obtained from its range in lead. The experiment was performed in two parts:

* This work supported by the joint program of the U. S. Atomic Energy Commission and the U. S. Office of Naval Research.
† Present address: Radioisotope Unit, Veterans Administration Hospital, Minneapolis, Minnesota.
[1] N. Bohr, Phil. Mag. **25**, 10 (1913); **30**, 581 (1915).
[2] H. Bethe, Ann. Physik **5**, 325 (1930); Z. Physik **76**, 293 (1932); F. Bloch, Ann. Physik **16**, 285 (1933); Z. Physik **81**, 363 (1933).
[3] See B. Rossi and K. Greisen, Revs. Modern Phys. **13**, 247 (1941).
[4] E. Fermi, Phys. Rev. **57**, 485 (1940).
[5] G. C. Wick, Nuovo cimento **1**, 302 (1943).
[6] G. Halpern and A. Hall, Phys. Rev. **73**, 477 (1948).
[7] R. M. Sternheimer, Phys. Rev. **88**, 851 (1952).
[8] T. Bowen and F. X. Roser, Phys. Rev. **85**, 992 (1952).
[9] A. Hudson and R. Hofstadter, Phys. Rev. **88**, 589 (1952).
[10] W. L. Whittemore and J. C. Street, Phys. Rev. **76**, 1786 (1949).
[11] L. Landau, J. Phys. (U.S.S.R.) **8**, 201 (1944).
[12] K. R. Symon, Harvard thesis (1948) published in *High Energy Particles* by B. Rossi (Prentice-Hall, Inc., New York, 1952).

(a) the relativistic μ mesons were selected as shown in Fig. 1 and (b) the nonrelativistic arrangement similar to Fig. 1 with the exception that 8 inches of Pb was placed above the telescope to absorb electrons. For the relativistic case two groups of energies were selected at a time and in this case there were a total of six groups of energy. For the nonrelativistic case two groups of energies were also run simultaneously, and for this case, only two groups were obtained. The meson energy is obtained from the differential range in lead. Column 1 of Table I is the average meson energy. The highest meson energy looked at is obtained by counting all mesons of range greater than 864.5 g/cm^2 and computing the effective energy by using the sea-level spectrum[13] modified by the fact that the experiment was performed beneath several feet of concrete. No correction has been made for multiple scattering in the lead or the accidental rate, which is relatively high in a differential experiment of this kind. However, these effects do not invalidate the conclusions drawn from the data.

TABLE I. Calculated energy loss in 5-cm xylene for several meson energies.

Average meson energy Mev	$t\frac{dE}{dx}$ (Mev) with density correction	E_p (Mev) no density correction	E_p (Mev) with density correction	$\bar{E}$ (Mev) with density correction
80	10.42	10.61	10.61	11.01
135	9.39	9.26	9.26	9.82
385	8.98	8.56	8.13	8.94
425	9.07	8.57	8.13	8.94
630	9.34	8.65	8.13	8.95
740	9.48	8.72	8.14	8.95
875	9.61	8.82	8.15	8.95
995	9.66	8.88	8.15	8.95
1400	9.88	9.09	8.15	8.95
3000	10.42	9.52	8.15	8.95

The energy loss is determined by measuring the pulse heights from the scintillation counter, and the light output is taken to be proportional to the energy loss. This proportionality of energy loss to light output does not break down until much lower kinetic energies than that used in this experiment. The work of Chow[14] shows that saturation of π mesons in phenylcyclohexane occurs at energies below 32 Mev.

The pulses from the scintillation counter were amplified and fed to the vertical deflection plates of an oscilloscope which was triggered by a threefold coincidence ABC. The pulse and neon lights indicating whether counters D, E, and F were discharged at the same time the threefold coincidence occurred were photographed. Counters D and E set the limits on the differential energy of the meson, and counters F were for the purpose of eliminating a fraction of the side showers. The pulse from the phototube was shaped to have a 2-μsec rise time and a 7-μsec decay time. The

[13] J. G. Wilson, Nature **158**, 415 (1946).
[14] C. N. Chow, Phys. Rev. **87**, 903 (1952).

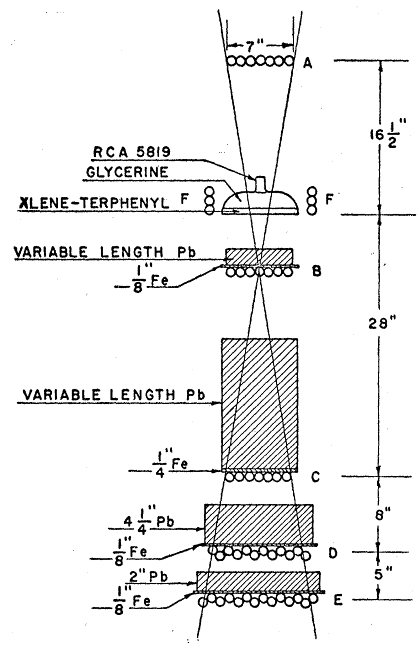

FIG. 1. Experimental arrangement. (Xlene should read xylene in the above figure.)

threefold coincidence generated a 20-μsec square wave with a rise time less than 1 μsec.

The liquid scintillator, which was 2 inches thick, was placed in a magnesium oxide coated hemisphere of 8 inches diameter. The upper section of the hemisphere was filled with glycerine for optical coupling and the photomultiplier was set into the hemisphere as shown in Fig. 1.

RESULTS

Pulse-height distributions for eight differential energy groups and for two integral energies have been obtained. The distribution obtained for mesons between 560 and 700 Mev is shown in Fig. 2. The distributions are typical of the distribution in energy loss as calculated by Landau[11] and Symon,[12] the major difference being in the much greater percent half-width of the experimental distributions. On the basis of Symon's work the calculated percent half-width in the energy loss distribution for a minimum ionizing μ meson in traversing 2 inches of xylene should be about 20 percent; however, the experimental relativistic distributions give a percent half-width of approximately 60 percent. The nonrelativistic distribution for a meson of energy 80 Mev is slightly broader than the relativistic ones. This might be explained by the fact that the distributions are differential, and in the nonrelativistic region before minimum ionization the energy loss is falling rapidly with increasing energy. The broadening of the experimental distributions can be accounted for on the basis of the following factors:

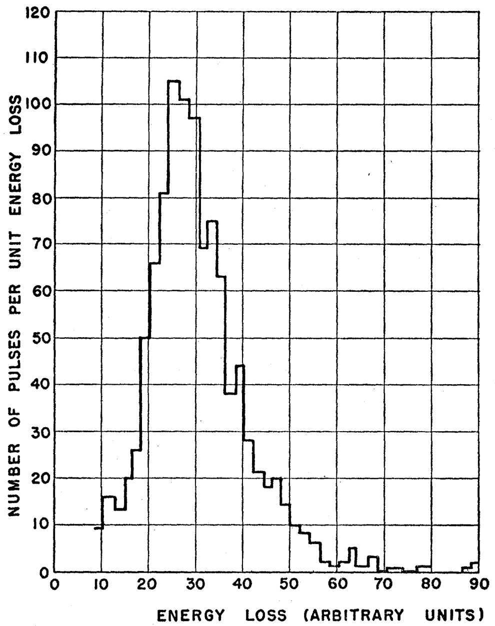

FIG. 2. Pulse-height histogram for meson energy 630 Mev.

(1) photoelectron statistics,

(2) difference in path length of the meson through the scintillator,

(3) attenuation of the light due to variations in the focusing from different parts of the cell,

(4) absorption by the liquid of its own radiation in varying amounts depending on source positions.

By measuring the gain of the photomultiplier at the voltage operated, the number of photoelectrons from the most probable pulse size has been calculated. From the work of Garlick and Wright[15] it is estimated that the photoelectron statistics has a full width at half-maximum of approximately 15 percent. The attenuation of the light at the photocathode was determined by measuring the output current from the photomultiplier when a polonium alpha source was placed in different positions of the liquid cell. This showed the light to fall off by a factor of two in going from the center of the cell to the end of the cell along any diameter. The weighting of this attenuation with the solid angle of the telescope and the cosmic-ray flux shows that the pulse-height distribution is shifted to the left, and that its standard deviation is increased. The exact value, however, is difficult to determine. The standard error if increased because of this large standard deviation or large half-width, but by taking more events the standard error can be made small. For all the differential energies used, the pulse-height distribution represents approximately 1000 events.

[15] G. F. J. Garlick and G. T. Wright, Proc. Phys. Soc. (London) **B65**, 415 (1952).

COMPARISON WITH THEORY

As discussed above, in order to compare the results with theory, we calculated the energy loss with a density correction in three different ways. The theoretical expression for the rate of loss of energy with the density correction as given by Sternheimer[7] is

$$\frac{1}{\rho}\frac{dE}{dx}=\frac{A}{\beta^2}\left[B+2\ln\frac{\beta}{(1-\beta^2)^{\frac{1}{2}}}+\ln T'+1-\beta^2-\delta\right], \quad (1)$$

where

$$A=0.15\times10^6\textstyle\sum Z/\sum A,$$

$$B=\ln(mc^2\times10^6\text{ ev}/I^2),$$

$$T'=\frac{E^2-\mu^2c^4}{\mu c^2(\mu/2m+m/2\mu+E/\mu c^2)}. \quad (2)$$

In this formula ρ is the density of the material, μ is the mass of the incident particle, m is the mass of the electron, E is the energy of the incident particle, I is the ionization potential of the material, δ is the density correction, Z and A are the atomic number and mass of the material. The ionization potential for xylene, I_x, was computed by using the following equation

$$\ln I_x=\frac{8\times6\ln I_C+10\times1\ln I_H}{8\times6+10\times1} \quad (3)$$

$I_C=76.4$ ev and $I_H=15.6$ ev are the ionization potentials of carbon and hydrogen, respectively.[16] The number multiplying $\ln I_C$ and $\ln I_H$ are weighting numbers obtained from the formula of xylene, which is C_8H_{10}. The density correction is obtained from the curves as given by Sternheimer.[7] For xylene, $A=0.0821$ Mev/g/cm^2, $I=58$ ev, and $B=18.8$. Column 2 of Table I is the product of Eq. (1) and the thickness of xylene in g/cm^2.

Using the Landau distribution we computed the most probable energy loss E_p, which is the peak of the distribution. The most probable energy loss for a small

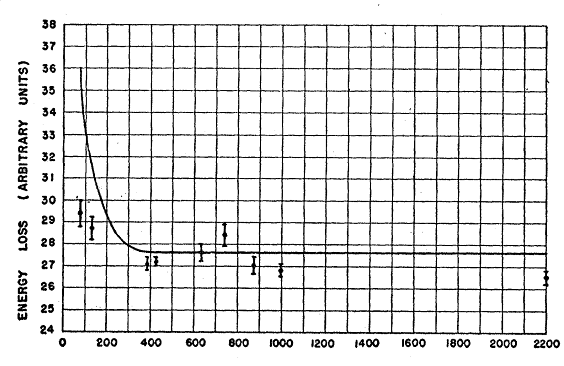

FIG. 3. The most probable energy loss as a function of meson energy. Solid curve—calculated with density correction.

[16] C. J. Bakker and E. Segrè, Phys. Rev. **81**, 489 (1951).

thickness of material, where by small thickness is meant that the average energy loss is less than one-tenth the kinetic energy of the incident particle, is

$$E_p=\frac{At}{\beta^2}\left[B+2\ln\frac{\beta}{(1+\beta^2)^{\frac{1}{2}}}+\ln\frac{At}{\beta^2}+1.37-\delta\right], \quad (4)$$

where t is the thickness of the material in g/cm². E_p for several meson energies is given in column 4 of Table I. It should be noticed that the rise in energy loss as given from Eq. (1) is much larger than is predicted by the most probable energy loss, Eq. (4), using the Landau distribution (thin absorber, skewed distribution).

The rise in energy loss, for μ mesons of energy 385 Mev and 3000 Mev, using the *Bethe-Bloch* formula with and without the density correction for 2 inches of xylene is 14 percent and 21 percent, respectively. This rise for mesons of same kinetic energy using the *most probable* loss of energy from the Landau theory with and without the density correction is 2 percent and 10 percent, respectively.

Using curves obtained from Symon's thesis[12] and knowing the most probable energy loss, the *median* energy loss $\bar{E}$ has been calculated. This median energy loss is that energy loss which divides the Landau distribution into equal areas, and it is not the same as the energy loss obtained from Eq. (1) by multiplying by thickness of the material in g/cm². The results of this calculation are given in column 5 of Table I, which shows the expected rise in median energy loss is 2 percent and 10 percent with and without the density correction.

For the nonrelativistic energies, 80 Mev and 135 Mev, the most probable energy loss was obtained from the experimental data by drawing a smooth curve through the experimental histograms. This was done by six individuals. The average of these six observations and the average error of these observations are the points plotted in Fig. 3. For the relativistic energies, a slightly different method was used to find the peak of the distributions. The peak of histograms of the relativistic energies were all in the same energy loss interval and so all the relativistic histograms were added together. From this histogram a smooth curve was drawn. The seven relativistic histograms were normalized to give the same area as the sum of all the relativistic histograms. Using the smooth curve obtained from the sum, the peaks of seven normalized histograms were found by observing how much the smooth curve had to be shifted along the abscissa in order to best fit the histograms. This operation was performed by six individuals, and the average of these results is plotted in Fig. 3.

The median energy loss was computed directly from the histogram data for the relativistic and nonrelativistic energies. The errors used are the standard errors, also obtained directly from the data. The result is plotted in Fig. 4.

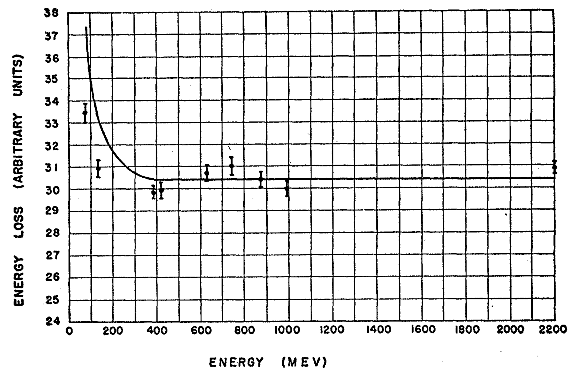

FIG. 4. The median energy loss as a function of meson energy. Solid curve—calculated with density correction.

The smooth curves in Figs. 3 and 4 are the calculated most probable and median energy loss using the Landau distribution with a density correction. The ordinate of Figs. 3 and 4 is in arbitrary units. The ordinates for the theoretical curves were found by normalizing the calculated median energy loss to the observed median energy loss at 385 Mev. One notes that when this is done, the curve representing the most probable energy loss falls, in general, slightly above the experimental points, but hardly outside the experimental error. One also notes that the experimental rise in energy loss cannot be as much as 10 percent and is not in disagreement with the theory corrected for the density effect.

The ratio of the median energy loss found by experiment for a meson of energy 80 Mev to the median energy loss for a meson of energy 385 Mev is about 15 percent too low if compared with theory. The ratio of an energy loss for mesons of 135 Mev and 385 Mev as found from experiment is about 8 percent too low. If this is evidence for saturation in the scintillator, it occurs at higher kinetic energies than found by Chow[14] for phenylcyclohexane. However, the range method used in this experiment presents greater difficulties in determining particle energy in this range due to scattering and other spurious effects, and more uncertainty is thereby introduced.

SUMMARY

The results of this experiment show that the rise in energy loss past minimum in a condensed material is in much better agreement with a theory[4–7] which takes account of the polarization of the medium. A comparison of the energy loss of a meson of 135 Mev with a meson of 385 Mev shows that an experiment of this nature can detect about a 3 percent change.

The authors are very grateful to Dr. Joseph W. Weinberg and Dr. Charles L. Critchfield for discussions on the theoretical aspects of this paper. We wish to thank Lenore Sausser for the construction of the Geiger counters used in this experiment.