μ-Meson Decay Spectrum*

J. H. VILAIN† AND ROBERT W. WILLIAMS‡
Physics Department and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received February 15, 1954)

The energy spectrum of positrons from the decay of muons at rest has been measured, using a synchrotron as the meson source and a magnetic-field cloud chamber as the spectrometer. A total of 830 tracks was obtained, and the relation between this sample and the true decay spectrum is discussed in some detail; difficulties which may have led to the discrepancies among previously measured spectra are pointed out. A strict set of selection criteria reduced the sample to 280 tracks; from this it is found that the spectral intensity does not go to zero at the upper energy limit, but retains a large value. In terms of Michel's parameter, $\rho=0.50\pm0.13$.

I. INTRODUCTION

ALTHOUGH the general nature of the energy spectrum of electrons from μ-meson decay has been known for several years,[1] the published results on the spectral shape do not agree among themselves.[2–5] The speculation that this process is related to beta decay, or indeed that all "Fermi interactions" are in some sense the same,[6,7] lends interest to a determination of the spectrum; several recent theoretical papers[8] have assumed that the spectrum goes to zero at the upper energy limit. We describe here an experiment[9] which shows that the spectrum in fact does not go to zero; in Sec. IV we point out some considerations which tend to bring previous results into consonance with this conclusion. The possible physical significance of this finding is also discussed in Sec. IV.

II. APPARATUS AND METHOD

A. Experimental Layout and Procedure

As a source we used π mesons produced by the action of the gamma-ray beam from the M.I.T. 330-Mev electron synchrotron on a block of paraffin. An expansion-type cloud chamber, mounted horizontally in a magnetic field of 9000 gauss, was used to observe both the incoming meson and the positron from the $\pi-\mu-e$ decay that occurred after the meson was brought to rest. The experimental arrangement is shown schematically in Fig. 1(a) (plan) and Fig. 2 (elevation): the paraffin target was placed in the fringing field of the cloud-chamber magnet; those positive mesons which emerged at approximately 90° with momentum in a broad band centered around 60 Mev/c entered through one cloud-chamber wall, crossed the chamber, and stopped in the opposite wall.

By adding considerable lead shielding we were able to obtain clean pictures with full synchrotron intensity and a large target; nevertheless, it was necessary to trigger the cloud chamber by counter control to obtain a satisfactory rate of usable pictures. For this reason, the cloud-chamber wall in which the mesons stopped was actually an anthracene scintillation counter backed by a pair of large Lucite light pipes which led to magnetically shielded photomultipliers. The cloud chamber was triggered whenever a large pulse in the counter was followed within one to five microseconds by another pulse. This event corresponded to the arrival of the meson (which in general stopped in the Lucite) followed by the delayed emission of a decay electron. Figure 1(b) shows a vertical section through the counter, which was

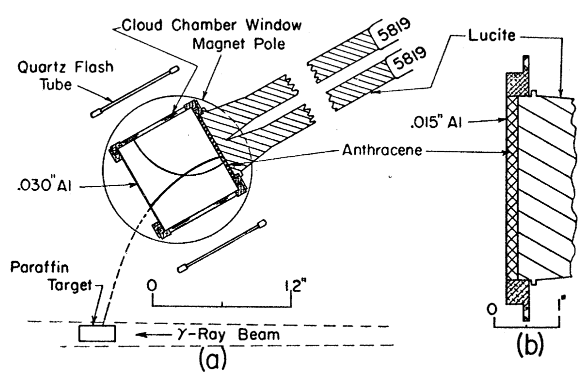

FIG. 1. (a) Plan view of the experimental arrangement, showing schematic trajectories of a meson and its decay electron. Shielding and thermal insulation are not shown. (b) Vertical section through the scintillation counter which comprises one wall of the cloud chamber.

* Supported in part by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.
† Present address: Ecole Nationale Supérieure de Télécommunications, Paris.
‡ Presently on leave at Princeton University, Princeton, New Jersey.
[1] R. W. Thompson, Phys. Rev. **74**, 490 (1948); J. Steinberger, Phys. Rev. **74**, 500 (1948) and Phys. Rev. **75**, 1136 (1949); Leighton, Anderson, and Seriff, Phys. Rev. **75**, 1432 (1949).
[2] A. Lagarrigue and C. Peyrou, J. phys. radium **12**, 848 (1951); A. Lagarrigue, Compt. rend. **234**, 2060 (1952).
[3] Sagane, Gardner, and Hubbard, Phys. Rev. **82**, 557 (1951).
[4] H. W. Hubbard, University of California Radiation Laboratory Report UCRL-1623, 1952 (unpublished).
[5] Bramson, Seifert, and Havens, Phys. Rev. **88**, 304 (1952).
[6] Tiomno, Wheeler, and Rau, Revs. Modern Phys. **21**, 144 (1949).
[7] L. Michel, Nature **163**, 959 (1949); Proc. Phys. Soc. (London) **A63**, 514 (1950); Phys. Rev. **86**, 814 (1952); L. Michel and R. Stora, Compt. rend. **234**, 1257 (1952).
[8] D. C. Peaslee, Phys. Rev. **91**, 1447 (1953); E. J. Konopinsky and H. M. Mahmoud, Phys. Rev. **92**, 1045 (1953); R. Finkelstein and P. Kaus, Phys. Rev. **92**, 1316 (1953).
[9] A brief preliminary report has already been given: J. H. Vilain and R. W. Williams, Phys. Rev. **92**, 1586 (1953).

a $\frac{3}{16}\times 3\times 6$ in. composite crystal. The illuminated volume of the chamber was $3\times 7\frac{1}{2}\times 7\frac{1}{2}$ in. (a square cross section was chosen to facilitate the introduction of the counter). An example of a meson and its decay electron is shown in Fig. 3.

The cloud chamber was thermally isolated and maintained at constant temperature by thermostatted circulating water. The magnet was maintained at nearly constant temperature by hand adjustment of a pressure regulator in the cooling water input. With this precaution we could assume that constant current meant constant field. The current was held constant to ± 0.3 percent (maximum fluctuation) by precise electronic control of the voltage across the magnet combined with half-hourly checks of the magnet current proper.

The value of the field was determined with a flip coil-G.E. fluxmeter-mutual inductance apparatus which was calibrated in fields measured by the proton resonance. The longitudinal field was mapped with the same device (it varied by ± 10 percent) and the radial field was calculated from this map.

We obtained 830 pictures which clearly show a meson and its decay electron, out of a total of 4350 pictures. This proportion, and the absolute counting rates, are in rough agreement with our geometrical estimates.

B. Selection Criteria and Measurements

We wish to examine a sample from the energy spectrum of positrons resulting from the decay of μ mesons at rest.[10] Since the point of origin of the (positive) electron is not visible, great care must be taken to choose the sample in an unbiased way. The lower limit of acceptable kinetic energy[11] was set at 20 Mev (15 percent of the spectrum lies below 20 Mev).

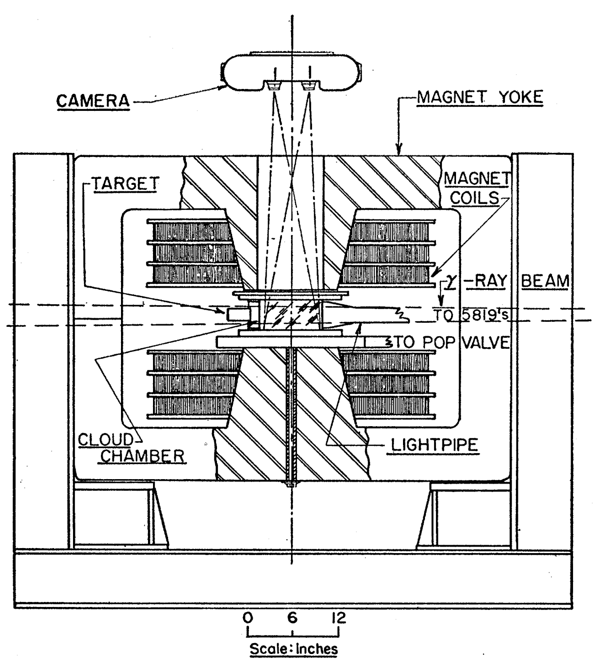

FIG. 2. Elevation of the magnet and cloud chamber with shielding removed.

[10] Negative μ mesons present a special problem because they decay from bound "atomic" states. See C. E. Porter and H. Primakoff, Phys. Rev. **83**, 849 (1951).

Each accepted event was required to pass the following tests: (a) the electron trajectory, extended back into the counter, must intersect the meson end point within prescribed limits; (b) the location and initial direction determined by this extended trajectory must be such that the electron would have had a path length in the Lucite plus anthracene of less than 4.2 cm (10-Mev energy loss) regardless of its energy (within the limits 20 Mev to 52.4 Mev); (c) the location and initial direction must be such that the electron would have had a visible track in the cloud chamber of more than 5 cm of arc regardless of its energy (within the limits 20 Mev to 52.4 Mev).

This procedure is intended to insure that each electron which is accepted would have been seen and accepted had it had any other energy within the limits, and therefore is part of an unbiased sample. It is straightforward and safe (with reservations as noted below), and sacrifices a large number of tracks in the interest of great reduction of the principal source of systematic error. The alternative would be to calculate an acceptance-and-resolution function which could not be checked by experiment.

Electrons of lower energy will suffer more scattering in the lucite, so that reconstruction of their point and direction of origin is less certain. For this reason the limits of intersection for test (a) were calculated individually for each track, and were set at $\pm$ two standard deviations in the horizontal plane and $\pm$ three standard deviations vertically. The distribution in space of the meson end point was determined from the meson momentum as measured on the cloud-chamber film, plus calculated straggling and scattering. About 10 percent of the mesons decayed to μ mesons before entering the cloud chamber, but these were readily recognized because they led to intersection points considerably deeper in the Lucite. Happily only seventeen events had to be rejected because of poor intersection. At the same time we verified that the selection was sufficiently severe to exclude accidentally space-coincident electrons, by calculation based on background runs (the probability proved to be small that there would be even one accidental in the entire sample).

A difference in reconstruction accuracy between low- and high-energy trajectories might be expected to have an effect on tests (b) and (c); however, the effects are such as to cancel out to a good approximation.

Of the 830 tracks, 280 were accepted. The tests described above were made on an orthogonal projection

[11] The great advantages gained by a fairly high cut-off energy are not accompanied by much loss in information. Since we cannot determine the shape of the spectrum in detail with only a few hundred tracks, we must try to find a one-parameter description of our data, and it turns out that the description chosen is insensitive to the part of the spectrum below 20 Mev.

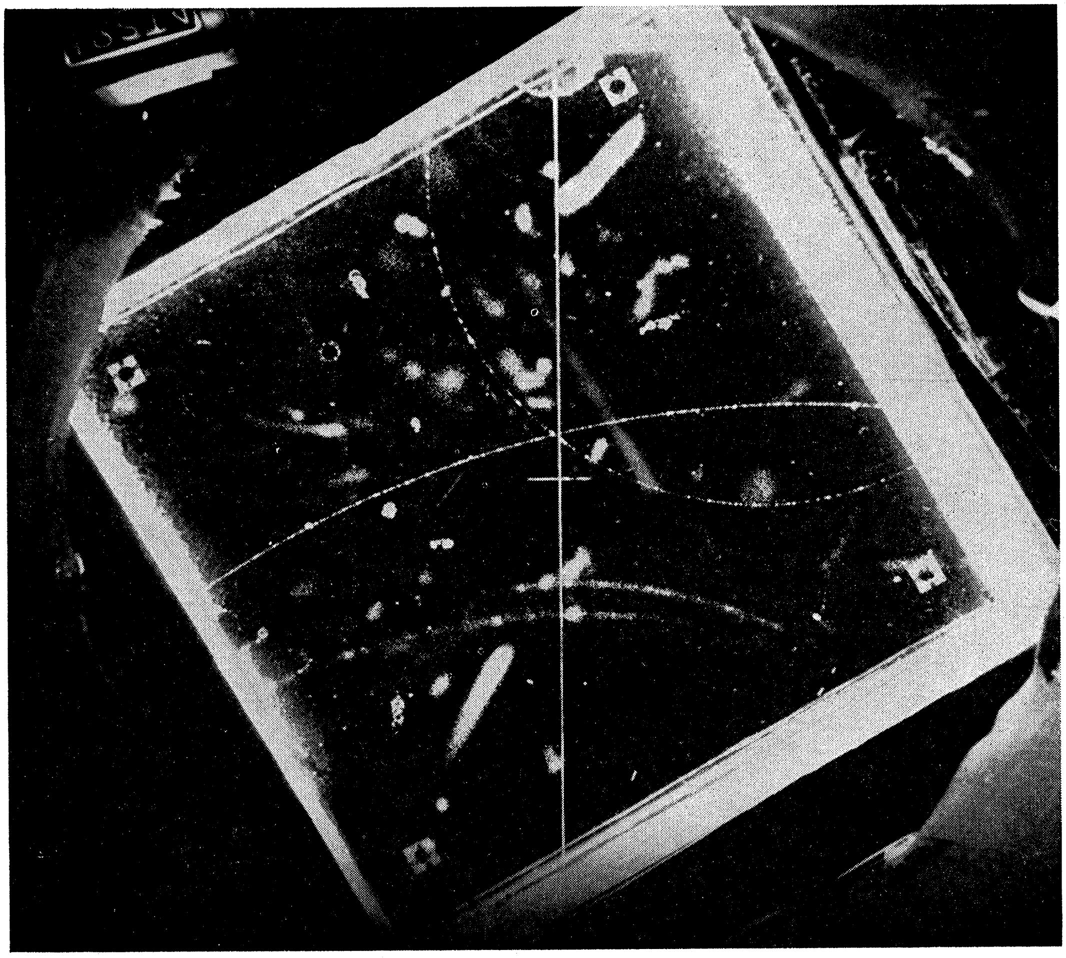

FIG. 3. Example of a meson (heavy track) and its associated decay electron (light track).

of the event.[12] To construct this projection and to supply geometrical information necessary to the determination of the electron energy we projected the two images of an event, through the lenses with which the pictures were taken, onto a translucent screen with one degree of freedom (vertical translation).

The observed momentum of each electron was computed from the curvature of its track image on the film. To achieve the necessary high accuracy, with tracks as short as 5 cm in many cases, it was necessary to measure track coordinates with a microscope fitted with a micrometer stage, and fit these coordinates to a circular arc. (Actually, of course, the coordinates are expanded, and fitted with an ellipse.) Because the track image is a conical projection of a helix (and, to a much lesser extent, because the magnetic field is not homogeneous) it will not actually be an exactly circular arc; the error we make by forcing a fit can be shown to average less than 0.1 percent.

Each track was corrected for the first-order effects of conical projection (average ±6 percent) and radial component of magnetic field (average ±0.7 percent). Average values for the second-order corrections, which are systematic, were found and applied to the sample as a whole; the largest terms were +0.37 percent and −0.26 percent. Momenta were computed from both right and left views for a few tracks; the agreement was within the expected errors, so the bulk of the measurements were made on one view only.

From the coordinates of five or seven points along the track (corrected for the motion of the gas during expansion) values of the magnetic field were read off, and the effective field computed by the method of Ascoli.[13]

To the energy of the electron as seen in the cloud chamber one must, of course, add the energy lost in the

[12] It might appear that test (c) involves consideration of those tracks that disappear out the top or bottom of the chamber as well as out the sides. One can easily show, however, that the length of arc of such tracks is independent of the momentum of the particle.

[13] G. Ascoli, thesis, Massachusetts Institute of Technology, 1951 (unpublished). We are indebted to Dr. Ascoli for sending us an elaboration of his elegant calculation.

lucite and anthracene. We used the calculation of Halpern and Hall[14] for water as a basis for our "collision loss" correction (which includes Čerenkov radiation). The average collision loss was 6 Mev; the upper limit allowed by our selection criteria was 10 Mev. Energy loss by bremsstrahlung presents a quite different problem: the most probable loss is zero but the average loss is quite appreciable, and fluctuations are large. The average path length in solid material, in our experiment, was 0.069 radiation lengths. Since the bremsstrahlung loss for each electron is not known, one must apply a bremsstrahlung distribution function to the family of theoretical (or empirical) spectra, and compare the resulting "folds" with the data. We have done this, using the calculation of Eyges.[15]

C. Estimate of Errors

We shall assume that the procedures outlined above have eliminated any possible sources of bias, and shall discuss here only errors in energy determination. Our estimates of the standard deviations describing important sources of uncertainty are detailed in Table I under the headings "Random" and "Systematic." Among the former, evaluation of the turbulence error presents some problems for a horizontal cloud chamber. We have measured counter-age tracks of cosmic-ray mesons of large zenith angle; the figure 1.5 percent is then an upper limit, since all of the measured curvature of these tracks is ascribed to turbulence, whereas in fact some of it is true magnetic deflection. The figure for multiple scattering corresponds to our gas filling of 1.3 atmospheres of argon. The combined random error of about 6 percent standard deviation will affect both the value and the uncertainty of the parameter (ρ) which we wish to determine from the data. Both effects could be completely accounted for by folding a Gaussian function into the family of theoretical curves; however, the extensive numerical work did not seem warranted, and we have followed a simpler procedure outlined in Part D.

TABLE I. Standard deviations assigned to the principal sources of error, expressed as *percent of the electron energy*.

Random errors (%)		Systematic errors (%)	
Multiple scattering	3	Energy loss in solid	0.7
Curvature measurement	3	Magnetic field	0.4
Path length in solid	2.5	Magnification	0.3
Geometrical factors	2	Meson mass	0.3
Turbulence	1.5		
Combined error	6	Combined error	0.9

Among the systematic errors the meson mass, which determines the maximum energy W and therefore the energy scale, deserves special mention. Several recent determinations[16] of M_μ, M_π, and the ratio M_π/M_μ are in good agreement with a value of $M_\mu = 207.0$, and a standard deviation ± 0.6 does not seem unduly optimistic.

D. Statistical Analysis

Determination of a spectral shape in this type of observation depends on resolution—in which we include the effects of biases—and the number of counts which make up the sample. Since we have in general sacrificed the number of counts available in order to obtain good resolution, we cannot trace the shape of the curve in detail, but must determine one free parameter in a family of theoretical or empirical curves. If the decay scheme is assumed to be[17] $\mu \rightarrow e + \nu + \nu$, the energy spectrum which is calculated from a direct-interaction theory, in analogy with beta-decay theory, is[7]

$$P(E) = \frac{E(E^2-1)^{\frac{1}{2}}}{A+\eta B}\left[3(W-E)+2\rho\left(\frac{4}{3}E - W - \frac{1}{3E}\right) + 3\eta\left(\frac{W}{E}-1\right)\right]dE,$$

where E is the electron total energy in units of M_ec^2, W its maximum value, $W = \frac{1}{2}[M_\mu c^2 + (M_e^2c^2/M_\mu)] = 52.9$ Mev, $A+\eta B$ is a normalizing factor depending on W, and ρ and η are functions of the coupling constants introduced in the theory; $0 \leqq \rho \leqq 1$; $-1 \leqq \eta \leqq 1$). The term involving η is small except for small E, where the common factor is small, so that it is a reasonable approximation to ignore this term, neglect 1 with respect to E, and obtain

$$P(E)dE = 4(E^2/W^4)\{3(W-E)+2\rho[(4/3)E-W]\}dE.$$

This has become the standard form for interpreting experiments on μ decay.

This spectrum, folded with the bremsstrahlung loss and renormalized to the interval $0.4 \leqq E/W \leqq 1$, is shown for three values of ρ in Fig. 4. On the same graph our results are plotted in histogram form; it is clear by inspection that of the three curves only $\rho = 0.5$ will fit the data. To obtain quantitative results for the best value of ρ, and its standard deviation, we have available several standard procedures of sampling theory. The most efficient procedure (in the sense that the standard deviation is smallest) is the method of maximum

[14] O. Halpern and H. Hall, Phys. Rev. **73**, 477 (1948).

[15] L. Eyges, Phys. Rev. **76**, 264 (1949). The actual calculations are clumsy, because we apply the bremsstrahlung fold on the basis of an average path length, while we add the collision loss to each electron energy individually. Eyges' formula takes collision loss into account. We therefore have to add the average collision loss back on to the folded spectrum before comparing it with the data.

[16] Smith, Birnbaum, and Barkas, Phys. Rev. **91**, 765 (1953); G. Ascoli, Phys. Rev. **90**, 1079 (1953); Lederman, Booth, Byfield, and Kessler, Phys. Rev. **83**, 685 (1951) (ratio m_π/m_μ); Val L. Fitch (private communication) (m_μ from meson-atomic spectroscopy).

[17] Bransom, Seifert, and Havens, reference 5, have observed the annihilation of the positron in flight, thus proving that it is indeed an ordinary positron.

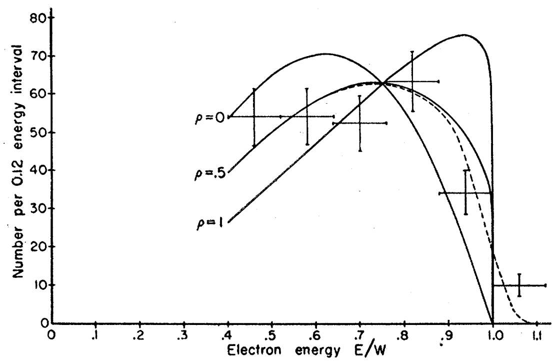

FIG. 4. Calculated spectra for three values of ρ, folded with the radiation-loss distribution function and normalized over the interval $0.4 \leqq E/W \leqq 1.0$. The dotted line shows the effect of folding in the resolution in energy measurement. The experimental data are lumped into numbers of events per 0.12 energy interval.

likelihood,[18] which maximizes the probability that this particular sample was drawn from the specified population.

Since this method is very tedious, we have first utilized the simpler method of comparing theoretical and experimental moments, to obtain a close approximation to the final answer. The moment method also affords an easy way to correct the results for the effect of the 6 percent random error in energy measurement. The dotted line in Fig. 4 shows the $\rho = 0.5$ spectrum after folding in the error; the calculated reduction in ρ is 0.05. Results from the second, third, and fourth moments are $\rho = 0.46$, 0.50, and 0.51, respectively. The corresponding[19] value from the maximum likelihood method is $\rho = 0.49 \pm 0.10$.

To see how large an effect the bremsstrahlung correction made, we calculated ρ assuming no radiation loss, and found $\rho = 0.31 \pm 0.07$. Since this represents a large correction, its accuracy was checked by dividing the data in half according to whether the path length in solid material was greater or less than the median. The resulting values of ρ agreed with each other within 0.01, showing that the correction is sound.

The spectrum with which we compare our data has been calculated with neglect of radiative processes. However, an approximate evaluation of the energy lost to "inner bremsstrahlung"[20] shows that it averages about 0.6 percent of the maximum energy of the electron. This will reduce the measured value of ρ in a way which depends somewhat on how the data are analyzed; in our case we find that our measured ρ should be raised by about 0.01 to 0.50.

Finally, the standard deviations in ρ caused by the 6 percent random error and 0.9 percent systematic error in energy measurement are computed to be ± 0.04 and ± 0.072, respectively. The combined standard error in ρ is, therefore, $(0.10^2 + 0.04^2 + 0.072^2)^{\frac{1}{2}} = 0.13$.

III. RESULTS

The analysis of the preceding section leads to the value $\rho = 0.50 \pm 0.13$, which means that the energy spectrum of the decay electrons is well represented by

$$P(E)dE = \left(8\frac{E^2}{W^2} - \frac{20}{3}\frac{E^3}{W^3}\right)\frac{dE}{W}.$$

This spectrum is shown in Fig. 5, along with the spectra $\rho = 0$ and $\rho = 1$ for comparison. Taking the maximum kinetic energy, $W - M_e c^2$, as 52.4 Mev, the average energy is 35 Mev, and the most probable energy is 42 Mev. Geometrically, ρ is just $\frac{3}{8}$ times the intercept of the normalized spectrum at the maximum energy, and we see that this intercept is quite high, nearly as high as the maximum point of the curve.

The principal contribution to the standard deviation in ρ is the statistical fluctuation due to the finite size of the sample; in the limit of large numbers (which our sample fulfills fairly well) this leads to a normal (Gaussian) distribution for the probability that ρ has a value different from 0.50. Since the magnitudes of the systematic errors have been included in a fairly conservative way, we feel that the quoted combined error can safely be regarded as describing a normal distribution; in other words, the chance that ρ will be as high as 0.75, for example, is about 0.03; the chance that it will be zero is less than 10^{-4}.

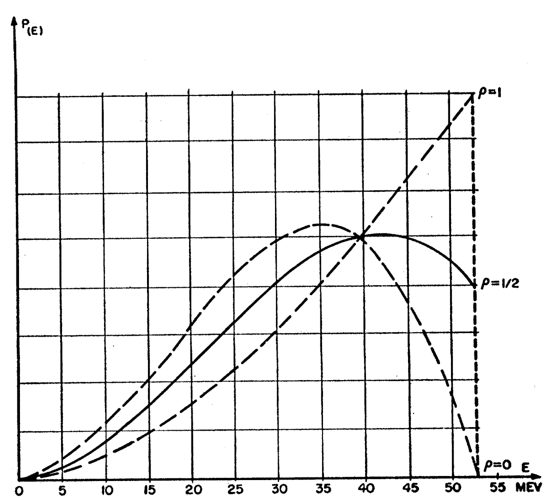

FIG. 5. The spectrum of decay electrons as determined by this experiment is the solid curve, $\rho = \frac{1}{2}$. Dashed curves show $\rho = 0$ and $\rho = 1$ for comparison.

[18] H. Cramer, *Mathematical Methods of Statistics* (Princeton University Press, Princeton, New Jersey, 1951), p. 498.

[19] Actually the maximum-likelihood calculations were finished before we corrected the meson mass from its old value ($209m_e$). We computed the change in ρ caused by this scale change by use of the moment method.

[20] A. Lenard, Phys. Rev. **90**, 968 (1953).

IV. DISCUSSION

A. Previous Work

The previously published[2–5] experimental results which yield quantitative statements about the meson decay spectrum are summarized in Table II. The column labeled "ρ corrected approximately for m_μ" is an estimate of the result expected if W had been taken as 52.9 Mev. The change in ρ for a change in W depends somewhat on the method of analysis: in our experiment $\delta\rho = -8\delta W/W$; in that of Bramson *et al.* $\delta\rho = -7\delta W/W$. Two points are clear from Table II: (a) the results as published are in definite disagreement, but the corrected results, except for the work of Sagane *et al.*, are in reasonable harmony with our result; (b) the correction can easily be quite large.

We suggest that the effect of error in the absolute energy scale (which includes both the value of the meson mass and the accuracy of the energy calibration) has not been treated adequately in the results shown in Table II, and that this fact is mainly responsible for the apparent discrepancies. Uncertainty in the energy scale (i.e., in W) may be treated as it has been in this paper, by an estimate of δW and its effect on $\delta\rho$; presumably the rather large error quoted by Hubbard[4] includes such an estimate. Alternatively, one may determine W from the data along with ρ, using a sort of internal calibration. This was done by Lagarrigue and Peyrou (the method is explained in reference 2) and presumably by Bramson *et al.*[21] However, determination of *two* parameters from the same set of data results in a larger statistical error for each of them, and this consideration was not included in the quoted errors. The same consideration probably applies to the work of Sagane *et al.*,[3] who derive values for both W and the intercept [which is $(8/3)\rho$] from their data. Inspection of Fig. 4 will show that statistical fluctuations and instrumental resolution effects can easily mask a finite intercept,[22] if one does not know the maximum energy.

TABLE II. Summary of previous work, with approximate corrections for the new meson mass.

Experiment	ρ	Quoted error	W	ρ corrected approximately for m_μ
Lagarrigue and Peyrou[a]	0.19	±0.13	55 Mev	~0.4
Sagane *et al.*[b]	<0.06	···	53.5±2 Mev	<0.1
Hubbard[c]	0.26	±0.26	53.7 Mev	~0.4
Bramson *et al.*[d]	0.41	±0.13	53.6 Mev	~0.5

[a] Reference 2. [b] Reference 3. [c] Reference 4. [d] Reference 5.

[21] No explanation is given in reference 5, but this method is implied in a previous note; see H. J. Bramson and W. W. Havens, Phys. Rev. **83**, 861 (1951).

[22] It was reported at the Rochester Conference on High Energy Physics, January, 1954, that the resolution of Sagane's instrument has now been improved to the point where the finite intercept is visible.

B. Goodness-of-Fit Tests

The histogram of Fig. 4 does not correspond very closely even to the "best" curve, $\rho = 0.50$. We have therefore made a χ^2 test to determine whether it is likely to get a sample which deviates at least this much from the parent population. The result is that there is about one chance in four of such a deviation, so it represents a quite normal fluctuation.

The curve for $\rho = \frac{1}{2}$ resembles rather closely the spectrum which is calculated purely on a statistical weight basis,[23] in analogy with the "allowed spectra" of beta decay. (The statistical spectrum contains a term in E^4, and therefore does not correspond exactly to any value of ρ.) Applying the χ^2 test, we find that our data could not distinguish between $\rho = \frac{1}{2}$ and the statistical curve; indeed, it would require at least 50 000 counts even with perfect resolution to distinguish between them. Evidently the agreement between the observed spectral shape and one form of the direct-interaction theory of μ-meson decay does not constitute a strong confirmation for that theory.

C. The Nature of the Interaction

The theory of μ-meson decay assumes, in analogy with beta-decay theory, that the interaction between meson, electron, and neutrino fields is a linear combination of the five invariant combinations of four Fermi-particle operators. The parameter ρ, which appears in the theory as a function of the five coupling constants, has a functional form depending on the ordering of the operators and on the question of distinguishability of the two neutrinos. A particular value of ρ, therefore, does not uniquely select one type of interaction (such as scalar, vector, etc.). Among the (infinitely many) combinations which will yield $\rho = \frac{1}{2}$ is the one for which there is no ambiguity associated with the ordering of the operators, the Wigner-Critchfield combination.[24] This interaction is antisymmetric under exchange of particles, and therefore is effectively independent of the order chosen for the operators. Aside from this symmetry property, however (whose physical significance is unknown), there is no *a priori* reason to suppose that the Wigner-Critchfield combination is correct.

The hypothesis of a universal Fermi interaction, i.e., that μ decay and beta decay are in some sense the same process, can be tested by inquiring whether the combination of coupling constants which explains beta-decay experiments can also lead to the correct value of ρ and the meson lifetime. Michel and Wightman[25] have recently investigated this question, for $\rho = 0.50$, and find that there are several combinations which make

[23] E. Fermi, *Elementary Particles* (Yale University Press, New Haven, 1951), p. 44.

[24] For a complete discussion of these points see reference 7, and also L. Michel, thesis, Sorbonne, 1953 (unpublished).

[25] L. Michel and A. S. Wightman, Phys. Rev. **93**, 354 (1954).

the two sets of data compatible. They point out, however, that recent theoretical attempts[8] to motivate a particular connection between the two processes (for example, by symmetry arguments) and therefore eliminate the remaining ambiguities, are in conflict with the experimental results.

The foregoing discussion is based on the assumption that the decay process is $\mu \rightarrow e+\nu+\nu$, where the two neutrinos may be either identical or distinguishable (for $\rho<0.75$ either case is possible). A finite rest mass for the neutral particles would be very hard to detect, since the difference between the observed and expected maximum energies, $\delta=W_0-W_{\text{observed}}$, cannot be measured with much precision unless one has an *a priori* knowledge of ρ; and even a small δ leads to a large value of the mass of the neutrals: $M_{\text{neutrals}}=(2M_\mu\delta/c^2)^{\frac{1}{2}}$. Thus an M_{neutrals} as large as 20 electron masses would go undetected.

V. SUMMARY

A reexamination of the experimental problems relating to a determination of the energy spectrum of positrons from μ^+ decay has shown that the result is critically sensitive to the combination of finite resolution and errors in the energy scale. Our finding is that the spectrum has a large intercept at the upper energy limit; in terms of Michel's parameter, $\rho=0.50\pm0.13$, where the standard deviation includes estimates of the systematic errors.

The often-mentioned striking similarity between μ decay and beta decay is not diminished by this result; however, no satisfactory answer is available to the question of the nature of the relation between the two processes.

ACKNOWLEDGMENTS

We are indebted to J. S. Clark and the entire synchrotron staff for their assistance and cooperation, and to Seymour Weiner for aid in building and operating the equipment. The initial design and construction of the experiment was mainly the work of V. P. Henri; G. de Saussure and D. A. Hill also contributed to its successful operation; many others have contributed both labor and valuable advice.

The completion of this work was made possible by the repeated leaves of absence which the French Service des Télécommunications generously granted to one of us (J.H.V.).

PHYSICAL REVIEW VOLUME 94, NUMBER 4 MAY 15, 1954

Cosmic Radiation Intensity-Time Variations and Their Origin. IV. Increases Associated with Solar Flares*†

JOHN FIROR‡
Institute for Nuclear Studies and Department of Physics, University of Chicago, Chicago, Illinois
(Received November 17, 1953)

The distribution on the earth of the impact points for particles of magnetic rigidities 1 to 10 Bv, which originally approach the earth from the direction of the sun, is derived, using principally the published results of numerical integrations of cosmic-ray orbits and model experiments on the motion of charged particles in a dipole magnetic field. Three impact zones for such particles are discussed. Two of these zones include only a small range of local times, and for the special case of the sun in the plane of the geomagnetic equator, are centered near 4 A.M. and 9 A.M. The third zone has no strong local time dependence. Assuming the source of charged particles to subtend a finite angle at the earth, the relative counting rates for detectors in the three zones are estimated. The counting rate due to particles from the sun is expected to be three to seven times larger in the morning zones than in the background, or nonlocal-time-dependent, zone. The morning impact zones are shown to have a seasonal motion of several hours in local time.

Reports of observations made during four large increases of cosmic-ray intensity at the times of solar flares are compared with the distribution predicted for particles from the sun. The observed increases agree with the predicted distribution and counting rate except at very high latitudes on the earth. A possible reason for this discrepancy is suggested.

Cosmic-ray data from the Climax neutron detectors are analyzed for possible increases associated with small solar flares. An increase of ≈ 1 percent is found for flares occurring when the detector is in a morning impact zone for particles from the sun. No increase of more than ≈ 0.3 percent is found for flares occurring when the detector is not in these zones. The mean daily cycle of cosmic-ray intensity is also shown to depend on the rate of flares occurring on the sun. The intensity curve is peaked during the early morning hours for flare periods relative to periods in which few or no flares occurred, in agreement with the supposition that new particles approach the earth from the direction of the sun at the times of flares.

I. INTRODUCTION

A. Time Variations of Cosmic Rays

It has long been known that the cosmic-ray intensity varies with time. Some terrestrial phenomena can be related to the cosmic-ray variations and that part of the variations eliminated (as in the case of the barometric pressure), but after carefully correcting for atmospheric effects there remains to date significant varia-

* Assisted by the Office of Scientific Research, Air Research and Development Command, U. S. Air Force.

† Based on a dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Physics, University of Chicago.

‡ Present address: Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington 15, D. C.

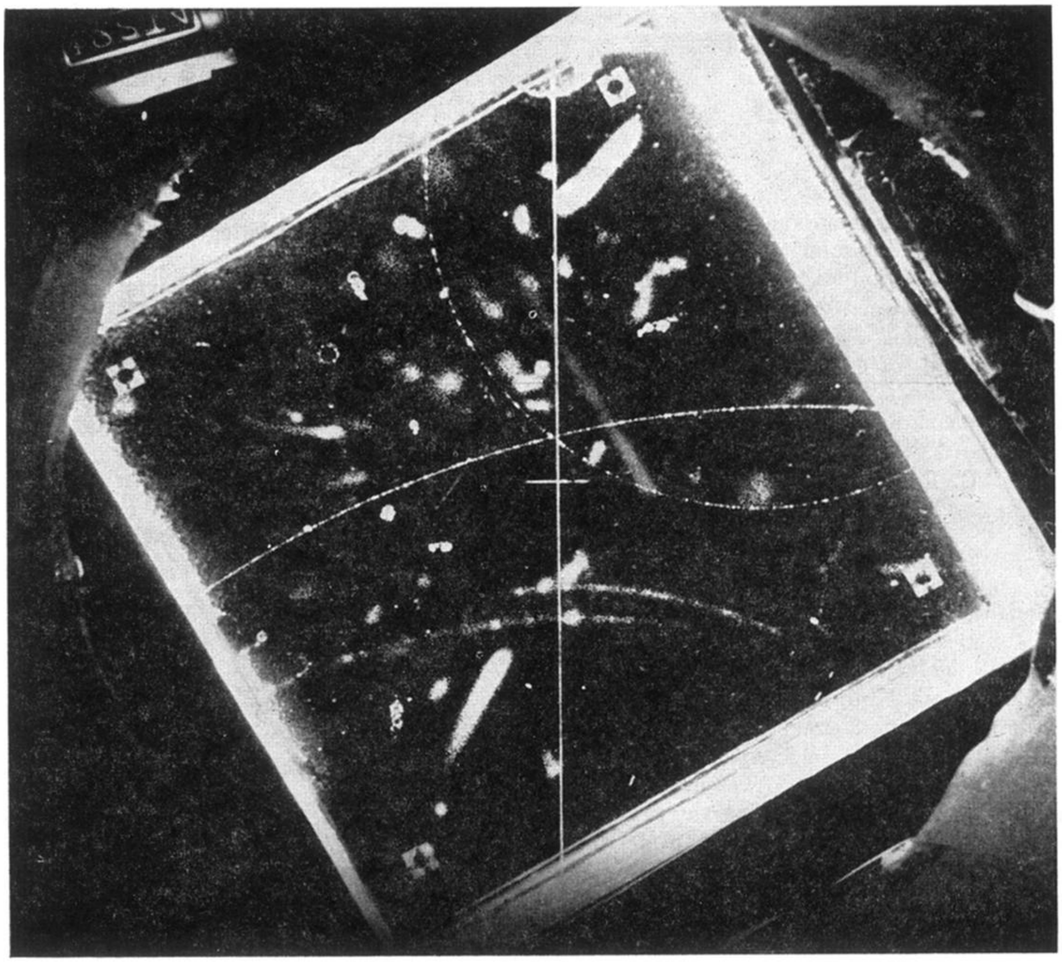

FIG. 3. Example of a meson (heavy track) and its associated decay electron (light track).