THE PROPERTIES OF MUON

談μ介子之性質

CHUNG-KAI CHANG

張 崇 愷

Department of Physics

Taiwan Normal University

I. Introduction

It was a great forward step to interpreat all of our material surroundings in terms of a few elements (now, we have already known about 103 kinds of elements and a lot of their isotopes). An obvious further step was the hope of interpreting these elements in turn in terms of two kinds of particles, the proton and the electron. As new particles were discovered this hope of the late 1920's slowly faded away, the number of recognized elementary particles was doubled with the discovery of the positron and the neutron in 1932. Information leading to the discovery of these was made possible by the development of modern techniques of studying the characteristics of particles, one of the most notable of these techniques being that of the the cloud chamber. With these improved techniques available still another particle was discovered in 1936 (Cf. below). This particle being called now the mu meson, or muon, is the first of the unstable particles to be discovered. Now, there are about 30 of the new fundamental particles have been discovered in cosmic radiation. Some were also produced later in the laboratory in reaction induced by artificially accelerated particles. Although among most of them we have still not known well about their properties, but we do have the evidence to identify their existence. The number may be much larger—conceivably infinite. Because most of the new particles are unstable and have very short half-lives, they are not easy to be detected. It is disturbing to have to hypothesize so many particles. What we need is a theory of matter that will allow us to predict the masses and other properties of them.

The muon, weighing some 200 times as much as an electron, above all the new particles is most tractable in the laboratory because of its relatively long life (2.2×10^{-6} seconds, Cf. below) and the case with which it can be produced. It has been studied in more detail than any other unstable particle. In this article, the writer intends to take a brief discussion on the properties and the decay modes of which this fundamental particle possessed.

II. Discovery of muon and its artificial production

Physicists had been looking for a particle of mass like the muon since its existance was pastulated by the Japanese theoretical physicist, Yukawa ①. He had shown that such a particle could explain the enormous strength of the forces that holds together the protons in the nucleus in spite of the mutual repulsion of their positive charges. The particle that accounts for the electromagnetic force field is the photon, which has no mass; by analogy, the nuclear force field should also have its particle, but this particle should have a certain amount of mass, because nuclear forces, unlike electromagnetic forces, extend only a short distance from the nucleus. The finite range of the nuclear force field indicated that its particle would have a mass about 200 times that of electron.

Shortly after Anderson discovered the positron from cosmic radiation, the same investigator and his co-worker ② announced that they had found still another unknown particle. They found that cosmic rays include electrical particles which make tracks in a cloud chamber much like those left by electrons, but which appeared to have other characteristics differing from those of the electron. These new particles were unusually penetrating; they did not knock electrons out of matter as readily as the usual electron; they often proceeded through lead plates without producing any perceptible secondary effects.

The evidence for existence of this new particle found by Anderson had come principally from two types of studies. Both of these have grown out of cosmic ray investigations. The one line of evidence came from studies of the rate of absorption of the radiation, and the other, from studies of the paths left by particles as passing through a cloud chamber. These studies have become sufficiently numerous that there can be no question as to the existence of a heavy electron (as named mu meson or muon) having a mass some 200 times the mass of the normal electron. ③

For several years the muons were thought to be the particle pastulated by Yukawa. But its weak-interaction (Cf. below) with nuclei and strong penetrating power through matter puzzled physicists who want to identify it with Yukawa's particle. The cosmic-ray muons is the most abundent component of sea-level cosmic radiation traveled easily through the atomosphere, penetrated lead plates and could even be detected in [illegible] mines. Such behavior was unbecoming to the hypothetical Yukawa particle. For to produce strong nuclear binding, Yukawa's particle must have quite strong nuclear interaction and therefore relatively small penetrating power.

This difficulty was resolved by Lattes et al. ④ who found another meson named as pi meson or pion), a component of cosmic radiation in the high atmosphere. Now, pion is regarded as the true Yukowa particle—its mass is about 270 m_e (electron mass), its spin integral, and its interaction with nuclei quite strong.

The pions of Lattes et al. are positive and negative charged particles with a mean-life of 2.5×10^{-8} seconds. This is in fact that the source of the muons that one finds at sea level in the cosmic radiation; a high energy nucleon incident at the top of the atmosphere collides with a nitrogen or oxygen nucleus and produces many pions, some of which decay into muons.

This fact leads to find a method to produce artificially the pions and the muons in the laboratory. If pions are the quanta of the nuclear force field, it ought to be possible to produce them by a strong acceleration of a nucleon, in much the same way as X-rays (light quanta) are produced when electrons are accelerated. The required acceleration can be produced in a nuclear collision, provided sufficiently energetic particles are available. To provide the rest energy corresponding to the mass of 270 m_e, nucleons of at least 135 Mev are required.

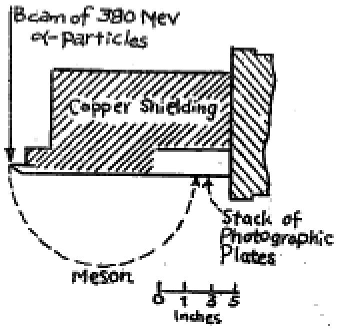

Fig. I. Target and detector arrangement for observation of artificially produced mesons. There is a magnetic field perpendicular to the figure. (Gardner and Lattes ⑥)

The first successful experiment of this kind was carried out with the Berkely

184-in. synchrocyclotron with a beam of 380-Mev α-particles bombarding a carbon target. ⑤ As shown in Fig. I, the cyclotron beam, circulating inside the dee, struck the edge of the target. Any negative meson ejected from the target in the forward direction would be deflected through a semicircle by the magnetic field of the cyclotron and would strike the detector. This detector consists of a stack of nuclear emulsions, set at an angle of [illegible] to the plane of the meson trajectory, so that mesons entering the surface would be stopped in the emulsions. A copious production of mesons was observed, as many as 50 useful tracks being obtained in each emulsion in a 10-min exposure. The mass could be determined from the curvature in the magnetic field and the range in the emlsion, proved to be about 300 m_e, indicating that the particles were pions. As was expected, the great majority of the negative pions which stopped in the emulsion gave rise to stars: no $\pi - \mu$ decays were observed. Laterly, the Berkely group ⑥ succeeded in detecting positive pions also, coming from the target. These they found almost invariably ended up by decaying into muons; in no case was star production by a positive meson observed.

It has been found that mesons can be produced with a variety of bombarding agents and target nuclei. Pions have been observed with α-particle, proton, neutron, and γ-ray bombardment of various elements, including hydrogen, beryllium, and carbon. But, we have not ever find a direct method to produce the muons artificially except those from the decaying of pions.

III. Charge of the muons

Both positive and negative muons are observed: at sea level there are about 20 per cent more positives. The magnitude of the charge can be determined with fair accuracy by a comparison of the specific ionization of high-energy muon and electron tracks, since the minimum ionization produced by such a partiele is proportional to the square of the charge.

In fact, the meson theory of nuclear forces implies strongly that the electric charge of a meson is exactly equal to that of a proton or electron. It is assumed that a proton, for example, can transform into a neutron with the emission of a positive meson. The meson takes off the electric charge. There is no reason to believe that any part of the charge can be created or distroyed, so that natural theoretical presumption is that the electric charge of a meson is exactly equal to that of a proton or electron.

The measurement of the charge of a muon has been made by Hazen ⑦. He compared the density of ionization of β particles from P^{32} with penetrating cosmic ray particles of momentum about 400 Mev/c. From his data it seems fairly sure that the ionization of muons does not differ from that of electrons by more than 10 per cent. Since the ionization is proportional to the square of the charge, the two charges cannot differ by more than 5 per cent.

Using the same general procedure, Frost's measurements ⑧ have reduced the possible difference somewhat further. As shown in Table I, the final column gives the ratio of muon charge to electron charge. In no case is it significantly different from unity, and the estimated errors indicate that the difference from unity cannot be greater than about 2 per cent. Another additional data obtained from the investigations of nuclear interaction of mesons (Cf. below) indicated that the muon charge is identical to the electron charge. Strong indirect evidence is obtained from the fact that different methods of measuring muon masses give consistent results if muon charge is assumed equal to that of an electron, and would not be consistent otherwise.

It should be remarked that no evidence has been found for the existence of a neutral muon. Presumably such evidence would be difficult to gather because a neutral muon would possess many of the properties of a neutrino. (Spin $\frac{1}{2}$, extremely weak interaction with matter, etc.)

Table I. Ionization by electrons and muons according to Frost ⑧

Gas	Minimum density of ionization for electron	Minimum density of ionization for muon	Ratio of min. density of ionization, muon to electron	Ratio of Charge, muon to Electron
Hydrogen	6.48	6.78	1.046	1.02 ± 0.03
Helium	8.13	8.20	1.009	1.005 ± 0.02
Argon	53.1	55	2.039	1.017 ± 0.03

IV. Mass of the muon

The mass of an energetic meson, like muon, is not easy to determine with precision. The curvature of the track of a meson in a magnetic field gives at once its momentum, since the charge is known. To find the mass, either the speed or the energy must then also be known. The speed can be inferred, if it is not too great, from the degree of ionization produced; the energy can be inferred from the range, provided the end of the trajectory can be located.

Leprince-Ringuet and his co-workers ⑨ made one of the earliest precise determinations of the muon rest mass. They were lucky enough to get a cloud-chamber picture that showed a muon in a magnetic field having an elastic collision with an element; just afterwards it passed through a lead plate with a measurable energy loss. Analysis of the collision gives 240 ± 40 m_e for the rest mass of the muon.

In the years 1946—1950 an extensive study of the masses of the mesons observed at sea level was carried out by Brode et al. ⑩. In these measurements, two cloud chambers, one above the other, were used. The upper chamber was in a strong magnetic field and served to determine the momentum of the particles; the lower was provided with a series of horizontal lead or copper plates in which the range could be determined. The result of these measurements was a mass of 206 ± 2 m_e ⑪.

The best "accelerator" value of the positive muon (μ^+) mass has been derived by Barkas ⑫ from a measurement of the mass ratio of the π^+/μ^+ meson (determined by magnetic curvature and range) and the value of the absolute momentum of μ^+ (derived from pions decaying at rest). Barkas finds $m(\mu^+) = 209.6 \pm 2.5$ m_e. The negative muon (μ^-) possesses the same mass as μ^+ within experimental error, according to a cloud-chamber measurement of Lederman et al. ⑬; by studying 25 $\pi^- - \mu^-$ decays in flight in a 16-in. cloud chamber subjected to a magnetic field, they derived a value 209.8 ± 2.2 m_e for the mass of μ^-, assuming the π^- mass to be 276.1 ± 1.3 m_e ⑭. More recent determinations of the mass of artificially produced positive muons give the value $m(\mu) = 207 \pm 1$ m_e.

The most accurate method of measuring the mass of muon, which must be combined with the measurement of the magnetic moment to obtain the "g-factor," ⑮ was first derived by L. J. Rainwatter. It consists of measuring the energy of X-rays (or photons) emitted when a negative muon cascades down through its allowable orbits around a nucleus. The energy follows the same laws that govern the energy of the photons emitted by electrons when they make similar transitions, and this energy depends directly on the mass of the particle. It happens that when X-rays are directed at an absorbing target, rays having a certain narrow range of energies are absorbed. These sharp changes in absorption, known as "edges," occur when an X-ray has just enough energy to knock an electron occupying a particular energy level clear out of an atom. By coincidence X-rays emitted by muon in a certain step of its cascade from orbit to orbit around a phosphorus nucleus have an energy corresponding to an edge in lead known as the "K edge." This edge is not absolutely sharp but changes over a narrow energy interval. By allowing X-rays from phosphorus mesic atoms to be absorbed in lead, one can determine just where is this energy interval the X-ray line is located. From this it is possible to calculate that the mass of the muon is 206.76 $\pm$ 0.2 m_e ⑯. While this is a remarkably precise value as mass measurements go, it still leaves a tantalizing uncertain of 10 per cent in the value of the "g-factor."

V. Spin of the muon

It has not yet proved possible to make any measurements of meson spin which are as direct and clear-out as those on the mass and charge. Theoretical considerations indicate that if the meson is responsible for nuclear forces it may well have a spin; since the nuclear forces are dependent upon the orientation of the spins of the nucleons involved, the meson field must, therefore, take account of those orientations in space. This cannot be done by a purely scalar field, but requires a field for which more than one quantity must be specified at each point. One way of accomplishing this would be to assign an internal coordinate which is to be specified in addition to the meson's position in order that its state be determined; that is, a meson spin.

Most experimental observations of particle spins are really observations of the effect of the magnetic moment associated with the spin. One observes, for atomic electrons, that the spectral lines are split up by applying a magnetic field, and one can then infer values of angular momentum and spin. The effect is observable because of the energy difference between different spin orientations in a magnetic field. The energy differences are small, however, and no one has noticed them in the case of mesons, whose energies, when observed, are usually many orders of magnitude greater than those of atomic electrons. In addition the number of mesons available to observe is usually of the order of "1", whereas in the case of atomic electrons it is 10^{15} or more. The problems involved are quite different, and the methods used for measuring spins of other particles have not so far been applicable to mesons.

As a matter of fact the most convincing information concerning muon spins has been obtained from that interactions of muons with other particles of known spin.

The various decay and absorption phenomena (Cf. below) in which the muon participates are all extremely suggestive of spin $\frac{1}{2}$ for the muon. In particular, the acceptance of zero cutoff at the high-energy end of the electron spectrum from muon decay as an experimental fact enables one to exclude spin 3/2 for the muon. This is so because all direct couplings of a spin 3/2 muon with a spin $\frac{1}{2}$ electron and two spin $\frac{1}{2}$ neutrinos lead to electron spectra with finite cutoffs ⑰. Spin 0 for the muon is also excluded since zero cutoff rules out all spin 0 theories except one, and the over-all shape of the electron spectrum from μ decay appears sufficient exclude this one possibility. These statements follow only if one believes the μ decay spectrum of Sagane et al. ⑱. If a finite cutoff turned to correct ⑲, after all, spin $\frac{1}{2}$ would still be plausible but the μ decay experiment would not constitute a measurement of the muon spin. The question still remains, therefore, whether there is any other type of experiment which yields a more direct determination of the muon spin.

Christy and Kusaka ⑳ were the first to point out that a careful analysis of certain cosmic-ray experiments on the frequency of large bursts of ionization produced by very energetic muons (the so-called "burst production" by the penetrating component of the cosmic radiation) would throw light on the muon spin. Their theoretical calculations showed that there were two processes by which mesons could create large electromagnetic showers, the production of high-energy knock-on electrons and bremsstrahlung photons. The latter process is the more important one.

The calculations with spin 0 or $\frac{1}{2}$ were a better fit to the experimental values than those with spin 1. They compared their calculations with the data observed by Schein and Gill. ㉑ As shown in Fig. II, the data appear to be in excellent agreement with the spin 0 case, but the accuracy of calculations and data is such as to rule out spin $\frac{1}{2}$. For one thing, the muon mass assumed in the calculations was 177 m_e. The bremsstrahlung cross section is inversely proportional to the square of the mass, as having been calculated for muons of spin 0, $\frac{1}{2}$, and 1, ⑳ so that use of the improved value of muon mass (215 m_e, by Brode), would reduce the calculated values by about 32 per cent ㉒, which would make the spin $\frac{1}{2}$ curve agree best with the experimental data. Other uncertainties render this conclusion uncertain as well. All that can be said is that spin 1 does not appear to be a possibility.

The main question concerning the experimental data is that of whether the bursts recorded really are showers created by muons. Qualitatively it is evident that this is the most likely process. There are four main possibilities for the production of bursts: (a) nuclear events (stars) in which heavily ionizing tracks are given off; (b) showers produced by mesons; (c) showers produced by high-energy photons or electrons; (d) groups of particles (air showers) incident on the ion chamber. (a), (c), and (d) are favored by going to high altitude, (a) and (d) tend to be important in thin-walled chambers where there is little chance for shower formation. Shower produced by muons appear to be the main cause of bursts in well-shielded ion chamber at sea level.

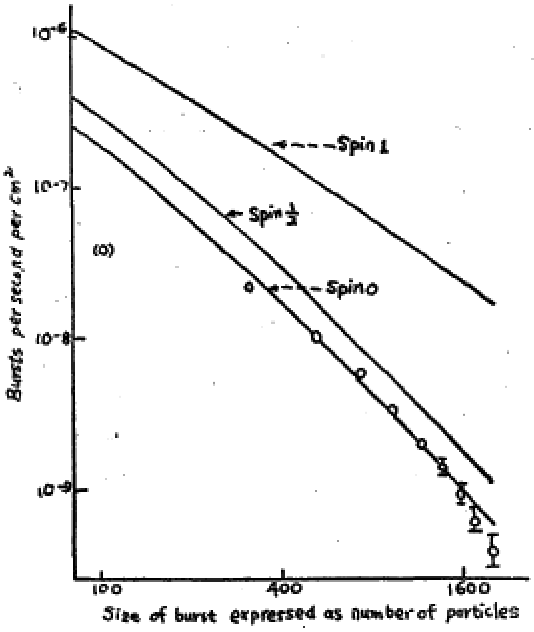

Fig. II. Calculated and Observed burst frequencies for different mesons, from Christy and Kusaka ⑳. Frequencies are given in bursts per cm^2 from a thick layer of lead. Sizes are given in number of particles, assuming the bursts consist of large numbers of minimum ionization particles. Circles are experimental points of Schein and Gill ㉑.

If high-energy mesons were the only cause of such bursts, one would expect the burst frequency to change very little between sea level and mountain altitudes. Schein and Gill ㉑ found, however, that the rate was several times as high at 3350 M. as at sea level. They interpreted this as an additional burst formation at the high altitude, probably due to high-energy photons and electrons. No such assumption is necessary at sea level since the calculations of Christy and Kusaka indicate that muons can account for all the bursts observed. If there is really a small contribution to the rate of occurence of bursts at sea level due to photons, electrons, or nucleonic component, this fact would make even stronger the conclusion that the muon spin is 0 or $\frac{1}{2}$, but not 1 or greater. These conclusions relative to bursts and muon spin have been substantiated by a more detailed investigation by Lapp ㉓. He has shown that bursts in ion chambers at sea level with shielding of 12 cm of lead and 35 cm of iron were both consistent with production by muons of spin 0 or $\frac{1}{2}$.

Fahy ㉔ has actually worked the argument the other way; assuming that the muon possesses spin $\frac{1}{2}$ (on the basis of the decay experiment), he infers from a comparison of the theoretical spin $\frac{1}{2}$ curve and the (d) curve in Fig. III that 55 per cent of the large bursts under 35 cm of iron at sea level are produced by muons. Since the theoretical spin $\frac{1}{2}$ curve is parallel to the experimental curve, it is reasonable to assume that the fractional contribution to burst production by muons is roughly constant over the range of burst size given. It follows, from the slope of the experimental curve that the integral muon spectrum in the energy region 10^{10} to 10^{11} ev is of the form $d\varepsilon/\varepsilon^{1.7}$.

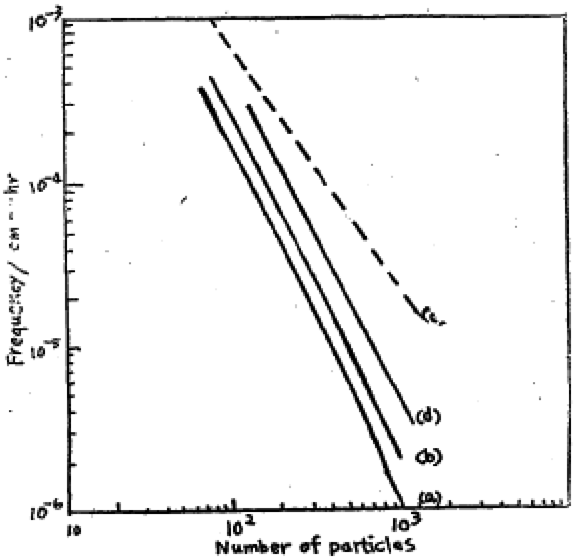

Fig. III. Theoretical frequency-size distributions for burst production corresponding to different assumed spins for muon; curve (a) corresponds to spin 0, (b) to spin $\frac{1}{2}$, (c) to spin 1. Curve (d) represents the experimental results of Lapp ㉓ at sea level using a 35-cm iron absorber.

Fahy ㉔ has measured the burst-production rate at an altitude of 3500 M. under thick absorbers consisting of (a) 10.7 cm of lead surrounding an ionization chamber and (b) 26.7 cm of lead surrounding the top hemisphere of the ionization chamber and 10.7 cm surrounding the bottom hemisphere. His integral size-frequency curves are shown in Fig. IV, together with sea-level curves obtained by Lapp ㉓ under 10.7 cm of lead. It is seen that there is a factor of 8.5 between the sea-level and mountain-altitude rates under a 10.7 cm lead absorber and a factor of 1.6 at mountain altitude between the two thicknesses of lead absorber. From the fact that 55 per cent of the burst production under 35 cm of iron at sea level is caused by muons and the assumption that the remaining 45 per cent of the burst-producing radiation which does not consist of muons is made up of a radiation whose cross section for burst production is proportional to $A^{2/3}$ (A is the atomic weight), it is possible to reduce that 68 per cent of the bursts obtained at sea level under 10.7 cm of lead are produced by muons.

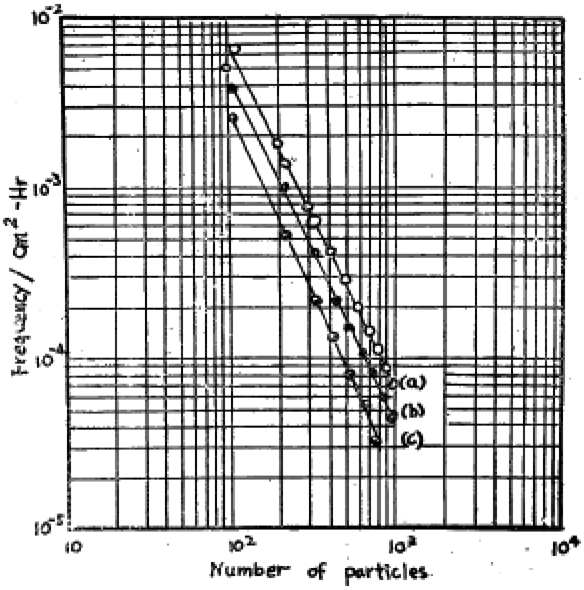

Fig. IV. Measured frequency-size distributions for burst production under different thickness of lead absorber and at two altitudes. Curve (a) corresponds to 10.7 cm of Pb at 3500 M., (b) to 26.7 cm of Pb on top and 10.7 cm of Pb on bottom at 3500 M., (c) to 10.7 cm of Pb at sea level.

As an over-all conclusion, then, we may say that a spin of 0 or $\frac{1}{2}$ seems to be indicated for the majority of muons at sea level, but this is by no meams an unalterable conclusion if strong contrary evidence should be presented. Other evidence presented in the decay of muon favors a spin of $\frac{1}{2}$. (Cf. below).

VI. Mean-life of the muon

According to Yukawa's theory, a free meson should decay into an electron (+ or −) and a neutrino; a meson which is captured by a nucleus should interact strongly with the nucleus and give rise to a violent disintegration. That the decay of the muon might be responsible for certain anomalies in the absorption of the hard component of cosmic rays was first suggested by Kulenkampff in 1938. It had been observed by a number of workers that cosmic rays are more strongly attenuated in the atmosphere than in condensed materials of the same equivalent thickness, measured in grams per square centimeter. This behavior could be accounted for if the meson in the atmosphere decayed with a life of the same order as the time required to stop them by ionization loss; in condensed materials, the time required to traverse a given number of grams per square centimeter is much smaller and the decay is less important.

In a series of experiments undertaken to provide quantitative data on this point, Rossi et al. ㉕ have measured the muon intensity at several altitudes in the atmosphere, and compared the apparent absorption with that observed in 87 grams per cm^2 of carbon. Since carbon has the same number of electrons per unit mass, and roughly the same atomic number as air, the true absorption due to ionization loss should be the same for layers of carbon and air having the same mass. The result of these experiments was that, at all altitudes, the apparent absorption coefficient in air is about twice as great as in carbon, indicating that about half of the loss of muons in air is to be attributed to decay. The mean life they obtained for the muons passing through their apparatus was $\tau = 3.2 \times 10^{-5}$ sec. In a coordinate system at rest with respect to the muon, the proper mean life τ_o is given by ㉖

$$\tau_o = \tau\sqrt{1-\beta^2} = \tau\,\frac{W_o}{W}$$

Where W is the total energy and W_o the rest energy, $M_o c^2$. The effective energy of the muons could be estimated from the known energy spectrum as 1.3 Bev. Thus from this experiment, the mean life of muon at rest was determined to be about $2.7 \pm 0.2 \times 10^{-6}$ sec.

A direct determination of the lifetime of muon at rest was undertaken by Rasetti and by Nereson et al. ㉗. They used the method of delayed coincidences and obtained the value $\tau^+ = 2.15 \pm 0.07 \times 10^{-6}$ sec. Alvarez et al. ㉘ have measured the lifetime of the μ^+ by detecting, with scientillation counters operating in delayed coincidence, the decay of the μ^+ arising from artificially produced π^+; they found $\tau^+ = 2.09 \pm 0.03 \times 10^{-6}$ sec. from a curve covering an intensity variation of a factor of 10^4. The different values agree within their statistical errors, and we may use 2.2×10^{-6} sec. as the lifetime of the muon.

According to the theoretical and experimental studies on the decay of slow μ^-, physicists ㉙ have already found the effect on the μ^- lifetime of competition from nuclear absorption. All evidence point to an equality of μ^- and μ^+ lifetimes in the absence of matter.

VII. Decay products of the muon

For a long time, it was thought that a muon decays into an electron and a neutrino, each departing with about 50 Mev apiece. In 1947, Anderson et al. (30) obtained two cloud-chamber photographs, each showing a muon decaying into an electron with an energy of about 25 Mev. Soon thereafter, many experimentalists secured evidence for the nonuniqueness of the electron energy (two-particle decay should lead to a unique energy), and it is now certain that the muon emits a continuous spectrum of electrons. This fact implies that the decay of muon is accompanied by the emission of at leat two neutral particles in addition to an electron.

Leighton et al. (31) have measured the electron spectrum from muon decay with a cloud chamber in a magnetic field of about 7,000 gauss exposed to the cosmic radiation; 75 decay electron tracks were measured, and it was found that the electron spectrum extends from 9 to 55 Mev. The observed upper limit of the spectrum implies a muon mass of 217 ± 4 m_e assuming the decay scheme

$$\mu \longrightarrow e + 2\nu$$

(ν is a neutral particle of mass 0, presumably a neutrino), although it was not clear, in view of the experimental error, whether the spectrum at the upper limit had a finite or zero cutoff. The mean electron energy turned out to be about 35 Mev (about one third of the muon rest mass) and therefore argued against more than two neutral particles (in addition to the electron).

Further evidence for a continuous spectrum was obtained by Davies et al. (32) using photographic plates. They measured the energies of 81 decay electrons and obtained a peak in the energy distribution somewhere between 35 to 40 Mev. The observed spread of energies was definitely outside the statistical spread which would have resulted from a single decay energy. The upper limit of the spectrum was not so sharply defined as in the cloud-chamber experiment but nevertheless led to a reasonable mass 204 ± 19 m_e for muon. Another photographic measurement of the electron spectrum from μ decay has been made by Bramson and Havens (19); thesr results, based on 117 decays, are shown in Fig. V. If the average electron energy is taken as one-third of the total available energy, the mass of muon can be inferred from Fig. V and turns out to be 209.3 ± 2.2 m_e. They believe that their points imply a finite cutoff at the high-energy end (in disagreement with Sagane et al. — Cf. below), although the statistical nature of multiple scattering measurements (by means of which the electron energies were determined) must make this conclusion questionable.

The most accurately determined electron spectrum from μ^+ has been obtained by Sagane et al. ㉝ using a spiral-orbit spectrometer. Their spectrum is shown in Fig. VI including the correction due to the finite resolution of the spectrometer. This experimental spectrum is in excellent agreement with the theoretical "Dirac" electron spectrum predicted from μ decay, which attains completely unique shape as following ㉞:

$$P(W)\,dW = G_\mu^2 \frac{\sqrt{W^2-1}}{4\pi^3} (D_s^2 + D_p^2)\,\mu\,(W_0 - W)\,dW$$

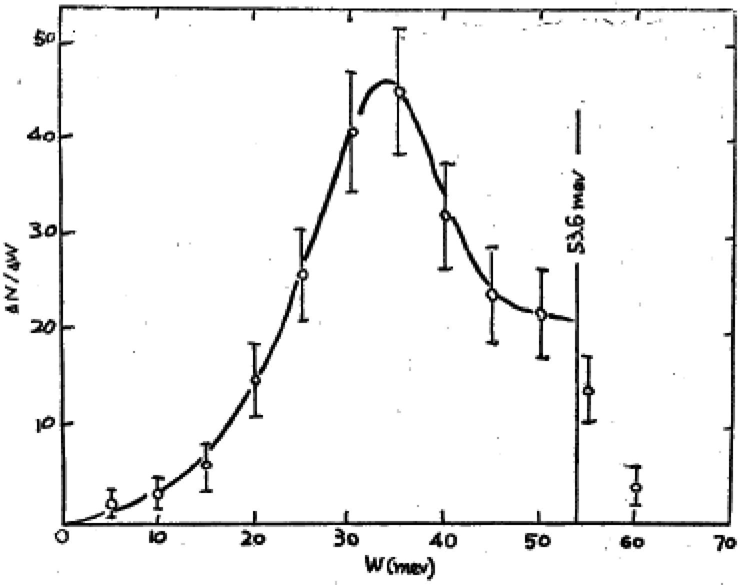

Fig. V. Measured electron spectrum from μ^+ decay (Bramson and Havens); the solid curve represents the best fit to the experimental points⑲.

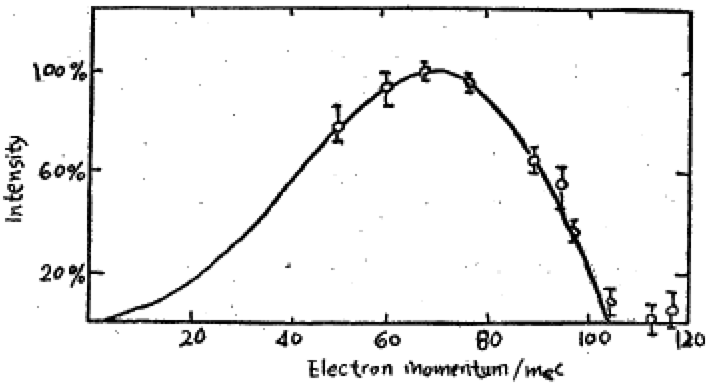

Fig. VI. Measured electron spectrum from μ^+ decay (Sagane et al.); the solid curve represents the theoretical "Dirac" electron-spectrum showing the best fit to experimental points ㉝.

It points out: (a) the maximum energy = 53 ± 2 Mev, from which one derives a muon mass = 212 ± 5 m_e; (b) the intensity is a maximum at 70 ± 3 $m_e c$ on a momentum scale; (c) the intensity is zero at the upper limit of the spectrum within the experimental accuracy (10 per cent of the maximum intensity).

The best demonstration that shows the charged particle resulting from the muon decay indeed possesses electronic mass, comes from an experiment by Hincks and Pontecorvo [35]. They investigated the penetration of the charged decay particles from muons through various absorbers, and found two components in the decay radiation, one of which was more penetrating than the other. The soft component is the charged particles whereas the hard component is the bremsstrahlung radiation associatied with the charged particles constituting the soft component. The actual intensity of the hard component requires a mass less than 2 m_e for the charged decay particle. Further support for the electronic nature of the charged decay particle from muon comes from an observation of the collision of one of the decay particles with an electron in a photographic emulsion and a measurement of the energies before and after the collision by means of the scattering method [36]. It turns out that the conservation law requires the charged decay particle to be an electron.

To identify the nature of the neutral particles resulting from the decay of a muon, Hincks and Pontecorvo [37] have performed a direct experiment (looking for coincidences between decay electrons and materialized γ rays) in order to decide definitely whether or not one of the neutral decay particles is a photon; but their result was completely negative.

All the quoted experimental results lead to the following unique decay scheme for muon $\mu^{\pm} \longrightarrow e^{\pm} + 2\nu$, where ν represents a neutrino. Myre recently, many experimental works [38] have identified the conclusion that a neutrino and an antineutrino are emitted in the decay of a muon, rather than two neutrinos or two antineutrinos. Several other decay modes of muons have been also predicted and investigated by many physicists [39], but it is still questioned to make a definitely successful conclusion.

VIII. Interaction of muon with matter

A muon interacts with matter through its electric charge and magnetic moment [40], and through the β-decay interaction. Therefore a muon loses energy through ionization of the matter through which it passes. In fact, ionization is virtually the only means by which muons lose energy, since their relatively large mass leads to quite small scattering by atomic nuclei, so that bremsstrahlung is quite unimportant, and their nuclear interaction is extremely weak. Due to this inertness muons leave them as the major constituent (about 80%) of the cosmic rays at sea level; and nucleons are removed by nuclear collisions.

If a muon is brought to rest by traversing matter, its fate depends upon its sign of charge ㊶. A positive muon, being repelled by atomic nuclei and attracted by electrons, may borrow an outer electron from an atom and with it make a hydrogen-like "atom", the muon being the "nucleus". This phase of its life is short; for the muon decays into an electron and two neutrinos with a mean life expectancy of but 2 μ-sec.

On the other hand, a negative muon is attracted by atomic nuclei and, in virtue of its mass being so much greater than that of an electron, it readily displaces an electron from an atom and forms what is called a "mesic atom". The meson drops from one bound state to another ㊷, emitting quanta as it goes, until it attains the ls-state. This capture process takes only about 10^{-13} sec., so that, once brought to rest in matter, nuclear capture is virtually certain. From this state the muon has two choices: It may decay into a negative electron and two neutrinos as it would do if free, or it may induce a β-transition in the nucleus by the process, which is so called "forced decay":

$$p^{+} + \mu^{-} \longrightarrow n + \nu$$

(where p^{+} is the proton and n is the neutron). The probability of occurrence of this kind of decay is found experimentally to vary approximately as Z^{4} for low and medium atomic number (Z), and to compete equally with spontaneous decay at $Z \approx 11$.

The energies of low-lying bound states of a mesic atom are virtually unaffected by the atomic electron cloud because the wave function of the meson is so strongly localized near the nucleus, but they are greatly modified by the penetration of the meson inside the nucleus itself. This property renders the muon quite valuable as a "test particle" with which to probe the structure of the nuclear charge distribution ㊸.

Another most interesting phenomenon which stems from the relatively great mass and small nuclear interaction of the muon is the mesic catalysis of nuclear reactions ㊹. Consider a μ-mesic hydrogen atom composed of a proton and a negative muon. This structure is quite small because of the large muon mass and, being neutral, is able to penetrate inside other atoms, just as a neutron can.

When the mesic atom closely approached another proton, the muon may be "shared" between the two protons to form a "mesic hydrogen molecule ion". The inter-proton distance of such a molecule will be comparable with the size of the charge cloud in the mesic hydrogen atom, namely, about

$$A_\circ = \frac{4\pi\varepsilon_\circ\hbar^2}{m_\mu e^2} = \frac{m_e}{m_\mu}\ a_\circ = 2.56\times10^{-13}\ \text{m}.$$

Although this separation is rather large compared with the "range" of nuclear forces, there may still be an appreciable probability of nuclear reaction between the protons within 2.2 μ-sec lifetime of the muon. If such a nuclear reaction does occur, the muon should usually be expelled, and might repeat the whole process.

Nuclear reactions of the above general type have been observed in the liquid hydrogen of a bouble chamber by Hugh Bardner ㊺ and are believed to result from the following sequence of events: A negative muon is brought to rest in the hydrogen and forms a mesic atom with a proton. This mesic atom wanders about till it encounters a deuterium atom (ordinary hydrogen contains about 1 per cent of deuterium), whereupon the muon leaves the proton and attaches itself to the deuteron. The mesic deuterium in turn wanders about until it forms an "H-D" mesic molecule ion, and the proton and deuteron combine to form ^{3}He, ejecting the muon with several Mev energy.

IX. The comparison between muons and electrons

Muons, electrons, and neutrinos are classified as a kind of light particles, called "leptons", whose interaction with baryons (or massive particles, namely, p, n, Λ°, Σ^+, Σ°, Σ^-, Ξ^-, etc.) and mesons (particles of intermediate mass, namely, π^+, π^-, π°, K^+, K^-, K°, etc.) is considerably weaker than that between baryons and mesons. According to this classification, muon is no more considered to be a meson ㊻.

Except the lifetime and mass, the muon in so far as the weak interactions go, behaves much like a heavy electron. As shown in Table II, there are many similarities between muons and electrons:

(a) There are two kinds of muons, positive and negative; as there are positive and negative electrons. There are no neutral muons and no neutral electrons.

(b) The muon's intrinsic angular momentum (spin) appears to be $\frac{1}{2}$, as is the spin of the electron. Curiously, the experimental evidence for this fundamental property is not strong, but since so many of the detailed properties of the muon satisfy the theory for a particle of spin of $\frac{1}{2}$, there seems little reason to doubt that $\frac{1}{2}$ it is.

(c) Both muons and electrons together with neutrinos, obey a conservative law stating that the number of leptons in the universe is a constant. This may seem strange inasmuch as there are many processes in which these particles are created and distroyed. If we count correctly, however, assuming the value of $+1$ to the electron, the negative muon and the neutrino, and a value of -1 to the positron, the positive muon and the antineutrino, then the number of leptons at the beginning and the end of any reaction is the same. For example, when a positive muon decays into a positron, a neutrino and an antineutrino, the total number of leptons is -1 both before and after the decay.

(d) The muon and the electron have approximately the same strength of magnetic moment. The value of the moment is often expressed in terms of a g-factor which is equal to the ratio of the actual magnetic moment in magnetons to a value that is half a magneton. The most recent measurement from the "g-2 apparatus" of C. E. R. N. (the European Organization for Nuclear Research) shows that the g-factor of the muon is $2.001145 \pm .000022$. The theoretical prediction is 2.001165. Experiment therefore confirms, to an accuracy of 1 per cent in the anomalous part of the g-factor, that the muon behaves exactly like a heavy electron.

The only baffling question is: If the muon is identical to the electron in its interactions, why should it be 200 times heavier? — Physicists believe that the mass of a particle is a consequence of its interactions; when two particles display identical interactions, there is no mechanism that can be invoked to explain a difference in their masses.

Soonafter the discovery of the breakdown of the parity ㊼, workers in muon physics now have a powerful means of studying this particle. A series of experiments have been initiated at Columbia Univ., the Univ. of Chicage and at C. E. R. N., to study the magnetism of the muon. It is of great interest to measure the magnetic mement of the muon ty determine if the theory that works so well for the electron is applicable. A deviation from the predicted value could give an important clue to the structure of the muon and hence to the origin of its mass.

The mystery of the muon mass has deepened and there are no very helpful suggestions as to where physicists can turn for enlightenment. The best hope seems to lie in scattering experimedts using the higher energy muons, for example, from the new 30-Bev accelerators at C. E. R. N. and at the Brookhaven National Laboratory. In such ultraenergetic collisions, there is always a chance that something new will be turn up to explain further the similarities between the muon and the electron.

Table II. The Comparison Between Muon and Electron

	Electron	Muon
Date Discovered	1897	1936
Mass	1	207
Mean Lifetime (Sec)	Infinite	2.2×10^{-6}
Electric Charge	−1 (+1)	−1 (+1)
Lepton Number	1 (−1)	1 (−1)
Spin	½	½
Modes of Interaction	Electromagnetic and "Weak"	Electromagnetic and "Weak"
Predicted Anomalous Magnetic Moment*	2.0011596	2.001165
Measured Anomalous Magnetic Moment*	2 .0011609 ±.0000024	2 .001145 ±.000022

*Expressed as the g-factor value.

References

(1) H. Yukawa, Proc. Math. Phy. Soc., 17, 48 (1935)

(2) C. D. Anderson and S. H. Neddermeyer, Phy. Rev., 50, 270 (1936)

(3) D. K. Froman and J. C. Stearns, Revs. Mod. Phy., 10, 176 (1938)

(4) C. M. Lattes, H. Muirhead, G. P. S. Occhialini, and C. F. Powell, Nature, 159, 694 (1947)

(5) E. Gardner and C. M. G. Lattes, Science, 107, 270 (1948)

(6) J. Burfening, E. Gardner, and C. M. G. Lattes, Phy. Rev., 75, 382 (1949); C. Richman, M. Skinner, J. Merrit, and B. Yantz, Phy. Rev., 80, 900 (1950)

(7) W. E. Hazen, Phy. Rev., 67, 269 (1945)
(8) R. H. Frost, Thesis, Univ. of Calf., (1947); quoted by R. B. Brode, Revs. Mod. Phy., 21, 37 (1949)
(9) L. Leprince-Ringuet, S. Gorodetsky, E. Nagestte, and R. Richard-Foy, Phy. Rev., 59, 460 (1941)
(10) W. B. Fretter, Phy. Rev., 70, 625 (1946); R. B. Brode, Revs. Mod. Phy., 21, 474 (1949); T. C. Merkle, E. L. Goldwasser, and R. B. Brode, Phy. Rev., 79, 926 (1950)
(11) quoted by B. Rossi, "High Energy Particles", p. 177
(12) W. H. Barkas, UCRL No. 1285
(13) Lederman, Booth, Byfield, and Kessler, Phy. Rev., 83, 685 (1951)
(14) W. H. Barkas, op. cit, No. 1285
(15) Cf., E. K. Richtmyer, E. H. Kennard, and T. Lauritsen, "Introduction to Modern Physics" (5th ed.), p. 287
(16) E. Segre et al., "Experimental Nuclear Physics", Vol. 1, p. 408, 1953
(17) E. R. Caianello, Phy. Rev., 83, 935 (1951)
(18) Sagane, Gardner, and Hubbard, Phy. Rev., 82, 557 (1951)
(19) H. Bramson and W, Havens, Phy. Rev., 83, 861 (1951)
(20) R. E. Christy and S. Kusaka, Phy. Rev., 59, 414 (1941)
(21) M. Schein, and P. S. Gill, Revs. Mod. Phy., 11, 267 (1939)
(22) R. B. Brode, Revs. Mod. Phy., 21, 371 (1949); Cf., Retallack, J. G. and R. B. Brode, Phy. Rev., 75, 1716 (1949)
(23) R. E. Lapp, Phy. Rev., 69, 321 (1946)
(24) E. F. Fahy, Phy. Rev., 83, 413 (1951)
(25) B. Rossi, N. Hilberry, and J. G. Hoag, Phy. Rev., 57, 461 (1940); B. Rossi, K. Greisen, J. C. Sterns, D. K. Froman and P. Koontz, Phy. Rev., 61, 675 (1942)
(26) Cf., Richtmyer, Kennard, and Lauritsen, "Introduction to Modern Physics", (5th ed.), pp. 61-63
(27) F. Rasetti, Phy. Rev., 59, 7061 (1941); 60, 198 (1941); N. G. Nerson and B. Rossi, Phy. Rev., 64, 199 (1943)
(28) Alvarez, Longacre, Ogren, and Thomas, Phy. Rev., 77, 752 (1950)
(29) Conversi, Pancini, and Piccioni, Phy. Rev., 71, 209 (1947); G. E. Valley, Phy. Rev., 72, 772 (1947); H. K. Ticho, Phy. Rev., 74, 1337 (1948); Harrison, Keuffel, and Reynolds, Phy. Rev., 63, 680 (1951); M. Creuch and R.

Sard, Phy. Rev., 85, 120 (1952)

(30) Anderson, Adams, Lloyd, and Rau, Phy. Rev., 72, 724 (1947)

(31) Leighton, Anderson, and Seriff, Phy. Rev., 75, 1432 (1949); Cf., R. W. Thompson, Phy. Rev., 74, 490 (1948); and, J. Steinberger, Phy. Rev., 75, 1136 (1949)

(32) Davies, Lock, and Muirhead, Phil. Mag., 40, 1250 (1949)

(33) Sagane, Gardner, and Hubbard, Phy. Rev., 82, 557 (1951)

(34) Cf., R. E. Marshak, "Meson Physics", pp. 212-213

(35) E. Hincks and B. Pontecorvo, Phy. Rev., 77, 1021 (1950)

(36) U. Camerini and P. Fowler, quoted in C. F. Powell, "Reports on Progress in Physics", 13, 350 (1950)

(37) Hincks and Pontecorvo, Phy. Rev., 73, 257 (1948)

(38) Cf., Garwin, Lederman, and Weinrich, Phy. Rev., 105, 1415 (1957); Feynman and Gell-Mann, Phy. Rev., 109, 193 (1958); Goldhaber, Grodzins, and Sunyar, Phy. Rev., 109, 1015 (1958)

(39) Cf., J. Tiomno, Phy. Rev., 76, 850 (1949); S. Lokanathan and J. Steinberger, Phy. Rev., 98, 240(A) (1955); R. R. Crittenden and W. D. Walker, Phy. Rev., 121, 1823 (1961)

(40) The magnetic moment of muon had been measured by Coffin et al. (Phy. Rev., 109, 973, 1958) as the value of 1.0026 $e\hbar/2m_{\mu}$.

(41) M. Conversi, E. Fancini, and O. Piccioni, Phy. Rev., 71, 203 (1947)

(42) Cf. H. A. Morwitz and M. H. Shamos, Phy. Rev., 92, 134 (1953)

(43) V. L. Fitch and J. Rainwater, Phy. Rev., 92, 789 (1953); L. N. Cooper and E. N. Henley, Phy. Rev., 92, 801 (1953); J. A. Wheeler, Phy. Rev., 92, 812 (1953)

(44) Alverez et al., Phy. Rev., 105, 1127 (1957)

(45) R. B. Leighton, "Principles of Modern Physics" (1959), p. 644

(46) Cf., Robert B. Leighton, "Princiyles of Modern Physics", (1959), p. 652; Gell-Mann and Rosenfeld, "Hyperons and Mesons: Systematics and Decay", Ann. Rev. Nuclear Sci., 7, 407 (1957)

(47) T. D. Lee and C. N. Yang, Phy. Rev., 105, 1671 (1957)