radio emission if the density of electrons with energy greater than 1 Bev is on the order of 3 $\times 10^{-13}$ cm^{-3}. The density computed from the measured electron flux is 1.3×10^{-12} cm^{-3}, which appears to be more than enough to account for the observations of galactic radio noise.

An upper limit for the flux of electrons arising from nuclear interactions of cosmic rays with interstellar hydrogen gas can be obtained from the data which were used earlier to determine the number of secondary electrons produced in the atmosphere. Although the average thickness of matter traversed by a cosmic ray within the galaxy is about 1 g cm^{-2} (this thickness is suggested as an upper limit by considerations based on the relative abundances of protons and heavy nuclei in the cosmic-ray beam), the number of electrons produced in this thickness of interstellar hydrogen is about the same as the number produced in the 4 g cm^{-2} of air above the balloon. This occurs because the interaction probability per g cm^{-2} for hydrogen is about twice that for air and because all of the μ mesons produced in space decay while only half of those produced in the atmosphere above the balloon do so. (The flux of gamma rays from interstellar nuclear collisions is very small compared to the electron flux because the time that the electrons are trapped by galactic magnetic fields is large compared to the time required for the gamma rays to leave the galaxy on straight paths.) If the mean distances traversed in the galaxy by protons and electrons are equal, the electron flux arising from nuclear interactions in interstellar space is no larger than the flux arising from nuclear interactions in the atmosphere above the balloon. Since this flux was estimated to be only 13 % of the total electron flux, it appears unlikely that all of the observed electrons arise from nuclear interactions of cosmic rays with interstellar hydrogen.

The author would like to thank Professor E. P. Ney for his interest in this investigation and Professor J. R. Winckler for his comments on the manuscript.

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*Supported by the joint program of the U. S. Atomic Energy Commission and the Office of Naval Research.

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MEASUREMENT OF THE ANOMALOUS MAGNETIC MOMENT OF THE MUON

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(Received January 16, 1961)

By storing polarized μ mesons in a magnetic field for as long as 1000 cyclotron periods it has been possible to measure directly the anomalous magnetic moment. We find the anomaly in agreement to within 2 % (that is, 2×10^{-5} accuracy on the total magnetic moment) with that expected from the quantum electrodynamics of a Dirac particle.

At present the muon appears to be a heavy electron with no interactions except the electromagnetic and the weak. This concept gives no explanation for the muon-electron mass difference, but allows the muon magnetic moment to be calculated from the Dirac equation and quantum electrodynamics as[1-6]

$$\mu = g(e/2Mc)\times(\hbar/2), \tag{1}$$

with $g\equiv 2(1+a)$, the anomalous part of the moment, a, being

$$a_{\rm th} \equiv (g-2)/2 = (\alpha/2\pi) + 0.75(\alpha^2/\pi^2) + \cdots = 0.001165, \tag{2}$$

with $\alpha^{-1}\equiv\hbar c/e^2 = 137.04$, the fine-structure constant of atomic physics. The first term in Eq. (2), $\alpha/2\pi$, arises from the emission and reabsorption of single photons, which alter the Dirac moment in two distinct ways, by the muon recoil, and by the muon spin-flip during the period of existence of the virtual photon.

A "breakdown of quantum electrodynamics," for instance a cutoff on the photon propagator at energy $\Lambda m_\mu c^2$, will modify Eq. (2) to (approximately)[7]

$$a = (\alpha/2\pi)(1 - \tfrac{2}{3}\Lambda^{-2}) + \cdots, \qquad (3)$$

while the existence of a "fundamental length" L, which might be expected to introduce cutoffs on the muon form factor and muon propagator, as well as on the photon propagator, will also introduce[8] a correction of form Eq. (3), but with $\Lambda \sim \hbar(4McL)^{-1}$.

Thus an experiment to a precision of 10^{-5} on g, or 1% of the a to be expected from Eq. (2), is sensitive to the behavior of the electromagnetic field alone to a distance of $\sim 3 \times 10^{-14}$ cm, and to the existence of a fundamental length as small as 7.5×10^{-15} cm. Since there is nothing special about a photon, other fields with which the muon interacts would contribute in just the same way to the anomalous moment, scalar fields giving only the recoil effect while vector fields yield also the spin-flip term. Thus a 1% experiment is sensitive to the existence of a coupling constant of order of magnitude 10^{-4} to a field of mass equal to that of the muon, or 10^{-3} for a field of mass equal to that of the nucleon. Of course, these coupling constants depend on the type of coupling assumed.

The magnetic moment of the muon has been measured[9] to high accuracy in absolute units, as has the muon mass[10,11] (needed for computing the muon magneton in order to calculate g). But to determine a to 1% of the expected value would require the mass to $<10^{-5}$ accuracy, which seems impossible even with the advanced techniques employed so far.

Fortunately there exists a direct way to compare the magnetic moment with the muon magneton using the principle employed for the electron by Louisell, Pidd, and Crane[12] and already applied very roughly to the muon by Garwin et al.[13] If muons are made to circle in a magnetic field, the spin turns $(1+\gamma a)$ times as fast as the momentum vector, with the result that after time t in a magnetic field B the relative angle between spin and momentum is changed by the amount $\theta = aB\omega_0 t$, where ω_0 is the cyclotron frequency for zero-energy muons in unit magnetic field.[14,15] We wish to report here the first precision measurement of the muon anomalous moment by this method.[16]

The muon mean life, 2.2 microseconds for a muon at rest, sets a limit to the storage time t which may be used. In fact, if the only loss is due to decay, the optimum storage time is two mean lives. In such an experiment the problems are therefore to know the direction of the polarization of the muons (relative to the momentum) before and after the precession time t, to know the mean field B, and to know the time t spent in the field, all to an accuracy considerably better than 1%. In fact, we record the polarization angle θ as a function of storage time t, since in our method muons have a range of storage times from 2.0 μsec to about 6.5 μsec.

In our scheme shown in Fig. 1, longitudinally polarized muons, formed by forward decay of pions in flight inside the cyclotron, are focused by a bending magnet and quadrupole pair into the

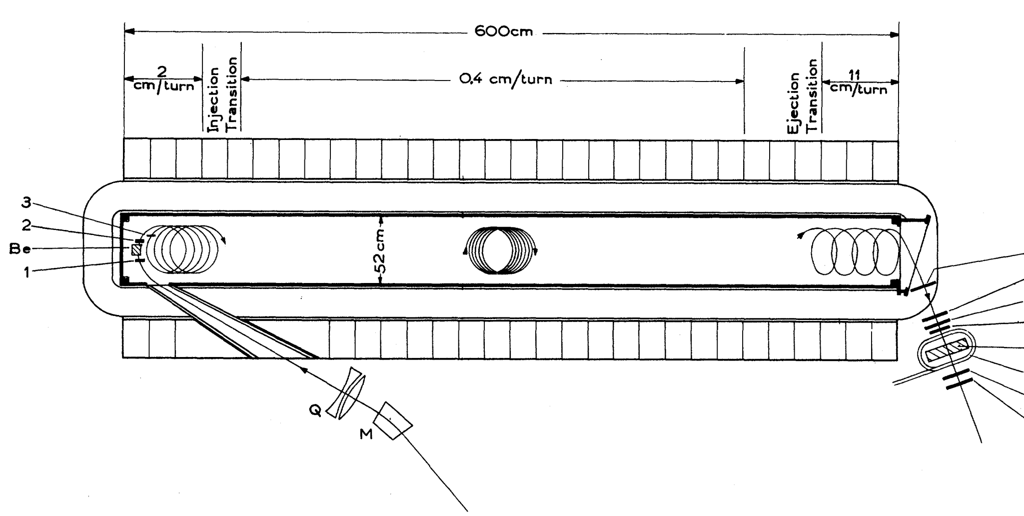

FIG. 1. General plan of the 6-meter magnet. M: bending magnet; Q: pair of quadrupoles; 1, Be, 2, 3: injection assembly consisting of Be-moderator and counters 1, 2, 3; T: methylene-iodide target; counters 66′, 77′: "backward" and "forward" electron telescopes. A stored and ejected muon is registered as a coincidence 4, 5, 66′ $\overline{7}$, gated by a 1, 2, 3 and by either a forward or backward electron signal.

entrance channel of the "6-meter magnet" and cross the center line ($y=0$) at roughly 90°. At this point the muons are moderated by a beryllium block to a mean energy corresponding to a radius of curvature R of 19 cm in the magnetic field B_0 of 15.8 kgauss. The field is not uniform but has at any x in the horizontal median plane the form

$$B(y)=B_0(1+ay+by^2+cy^3), \qquad (4)$$

in which the term ay produces a walking towards $+x$ with a "step-size" per turn, $S=\pi R^2 a$, where R is the orbit radius. The term by^2 with $b<0$ adds vertical focusing, and the term cy^3 changes the step-size to

$$S=\pi R^2(a+0.75cR^2), \qquad (5)$$

allowing one to choose c to give constant S for all R in the neighborhood of the mean radius. Such a field with $c=0$ and with a and b constant in x has been used at this laboratory with a smaller magnet to store muons for 25 turns and to measure their electric dipole moment.[17]

In the injection region, $S\sim 2$ cm/turn to allow considerable tolerance in alignment. A slow transition is then made to a weaker gradient giving a storage region with $S=4$ mm/turn, while in the ejection region the step-size is 10 cm/turn to allow the particle to cross the exit face of the magnet nonadiabatically and so to be ejected from the field. In practice the desired field shapes were obtained by shimming a magnet with flat pole faces with many layers of 0.5-mm steel shims. About 300 kg of shim is inside the magnet vacuum chamber.

Hall plate measurements showed that the necessary field form had been obtained, and the desired motion of the orbits was verified by studying the flux through a search coil of 18-cm radius, the flux through the walking orbit being an adiabatic invariant. The field is calibrated by proton resonance. A change of field of 0.1% from one end of the storage region to the other would produce a 2.5-cm sidewise displacement of the orbit and would lead to a considerable loss in intensity. By correcting local inhomogeneities by shims as thin as 0.03 mm, we achieved a field in which the orbits do not wander by more than ±1 cm laterally.

The timing to ~0.1% accuracy is done with a "digitron" developed from that of Swanson and Lundy.[18] Additional dead-time circuits are incorporated to remedy some minor defects in the original instrument and the timing is now referred to a 10-Mc/sec crystal oscillator. It is of great importance not only to time every muon to 1%, but also to reduce below 0.1% the probability of assigning the wrong injection count to an emerging μ, etc. The electronics which accomplishes this is too complex to discuss in full here, but it has a timing accuracy of 10^{-9} sec and a flat spectrum between random events to $\ll 1\%$; and it rejects completely all cases of doubtful parentage or progeny of no matter how high order.

The muons emerging from the magnet are stopped in a field-free region (<0.1 gauss) in a nondepolarizing, nonconductive target (methylene iodide). The electronics stores events associated with "backward decay electrons" (6-6′ coincidences with appropriate gating) in channels 1-50 of a CDC "pulse-height analyzer," as a function of the storage time t of the parent muon in the magnet (2.0-6.5 μsec); similarly events associated with forward decay electrons in telescope 7-7′ are classified according to storage time in channels 51-100. The muon spin direction is flipped in successive runs through ±90° in the 1.0 μsec following its arrival by means of a pulsed vertical magnetic field produced by an aluminum-tape coil wound on the target. From the counts c_{n+} and c_{n-} in the nth channel for ±90° flipping, one can compute independently for each channel an asymmetry

$$A_n=(c_{n+}-c_{n-})/(c_{n+}+c_{n-})=A\,\sin(aB\omega_0 t_n), \qquad (6)$$

where A is proportional to the polarization of the incident beam and t_n is the storage time corresponding to the nth and $(n+50)$th channel.

Figure 2 shows the observed data as well as the computed curve of the form (6) which fits it best. In actual practice the muons available for injection are not exactly longitudinally polarized. There is a transverse component which varies with range (~5°/g cm^{-2}), crossing zero at the peak of the range curve. This has been measured and included in the calculation, as has the angular distribution of decaying muons with respect to the normal to the polarization analyzer. The parameter $(g-2)/2$ for this best fit is

$$a_{\rm exp}=a_{\rm th}(0.983\pm 0.019)=0.001145\pm 0.000022, \qquad (7)$$

and the χ^2 for this fit is 13.5, in comparison with 9.7 expected.[19]

Of the 1.9% error quoted in Eq. (7), 1.7% is statistics, 0.6% comes from the uncertainty in the measured direction of the ejected beam, 0.6% from uncertainty in the part of the range spectrum (and hence transverse polarization) of the

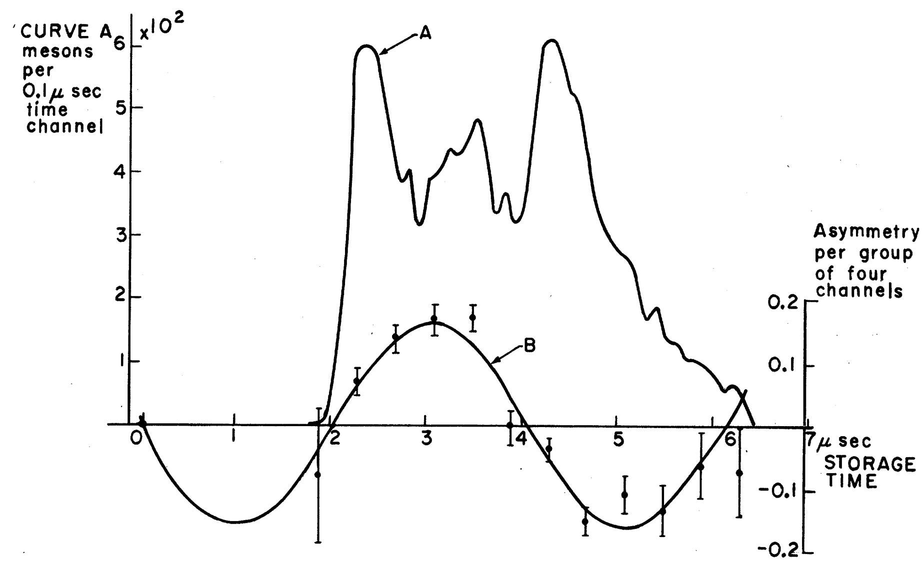

FIG. 2. Curve *A* (left-hand scale for ordinate): Storage-time distribution of muons that stop in the polarization analyzer and give rise to decay electrons. Curve *B* (right-hand scale for ordinate): The sinusoidal curve [see formula (6)] represents the best fit to the measured variation of the asymmetry with storage time. The curve must pass through the point near zero time, which is a very important datum for the fitting.

injected beam, and 0.3% from the statistical uncertainty in the initial polarization measurement.

We conclude that, using the available theoretical estimates,[1-8] and barring accidental cancellation of the effects on the muon moment, the following assertions can be made with 95% confidence:

(1) Conventional quantum electrodynamics is applicable to distances as small as 7×10^{-14} cm.

(2) The "radius" of the muon is less than 4.5×10^{-14} cm.

(3) No fundamental length exists with magnitude larger than 2×10^{-14} cm.

(4) The coupling constant $G^2/4\pi$ of the muon to an unknown field of nucleonic mass is less than $\sim3\times10^{-3}$, this limit varying approximately as $\lambda^2(\ln\lambda)^{-1}$, with $\lambda\equiv M/m_\mu$.

Combining our result with the muon precession measurement,[9] we obtain for the mass of the muon 206.77 ± 0.01 electron masses.

We wish to thank Professor G. Bernardini in particular for several decisions which were essential to the successful conclusion of this experiment, and Professor C. M. York for his close collaboration. Mr. B. Nicolai was of great technical assistance, as were R. Bouclier and L. Magnani. Professor W. K. H. Panofsky contributed very significantly during the fall of 1959. We are grateful to several physicists in this laboratory, in particular Dr. A. Petermann, for clarification of theoretical questions.

A more complete report, with details of the experimental techniques, of orbit theorems, etc., will be published.

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[19]The result (7) is the best least-squares fit to the data grouped in time channels 0.400 μsec wide. A maximum-likelihood solution for the anomaly has also been made on the IBM 709. The result is $a_{\rm exp} = 0.001144 \pm 0.000022$. The individual fits for forward electron telescopes and back are (with the full 0.100-μsec digitron resolution): $a_{\rm exp} = 0.001147$ (forward), $a_{\rm exp} = 0.001142$ (backward). To allow A in (6) to be an arbitrary linear function of the time changes $a_{\rm exp}$ by $\sim 1\times10^{-6}$.

ELASTIC SCATTERING OF LOW-ENERGY K^- MESONS ON PROTONS

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Following the CERN Conference in 1958[1] there was considerable interest shown in the possibility of a peak at ~30-Mev K^--meson laboratory energy in the elastic scattering cross section of K^- mesons on protons. Matthews and Salam[2] proposed an interpretation of the peak in terms of a $J=1/2$ resonance of the K^--p system. However, Jackson and Wyld[3] pointed out that the peak could also be satisfactorily understood on the basis of S-wave zero-range K^--p scattering theory and a repulsive K^--p nuclear interaction. The resonance proposal has also been discounted by Dalitz and Tuan[4] who pointed out that the effective range of the K^--p interaction would have to be unreasonably large in order to exhibit the observed elastic scattering cross sections at the low-energy values in the region of the so-called resonance.

At the Kiev Conference in 1959, bubble chamber results[5] were presented which no longer exhibited a peak in the low-energy elastic K^--p scattering cross section. However, further emulsion results[6] by the combined Bologna-Munich-Paris-Parma laboratories still tended to show the elastic cross-section flattening off at the lowest energies.

Emulsion data from the European K^- Collaboration groups[7] have now been carefully scrutinized for low-energy K^--proton elastic scattering events. All two-pronged events which could possibly be attributed to K^--p elastic scattering have been analyzed. Low-energy elastic scattering events on free protons can be readily recognized because these only will show coplanarity with complete balance of momentum and energy. Moreover, since the fraction of inelastic scattering events in which the K^- meson re-emerges from emulsion nuclei is known[8] to be only a few percent for energies in the range 30-100 Mev, there is a negligibly small chance of an apparent K^--p scattering occurring on an internal proton of an emulsion nucleus, especially for K^- meson energies below 10 Mev.

The results of our investigations, based on a study of 10 850 K^- mesons coming to rest and 2060 K^- mesons decaying or interacting in flight, are shown in Table I. Our results, which are shown with others of the bubble chamber[5] and emulsion[6] groups in Fig. 1, appear to indicate that the elastic K^--p scattering cross section is