Depolarization of Positive Muons in Condensed Matter*†

ROBERT A. SWANSON‡
The Enrico Fermi Institute for Nuclear Studies, The University of Chicago, Chicago, Illinois
(Received June 27, 1958)

The effects of parity nonconservation in the π-μ-e decay chain are used to measure the depolarization of positive muons in solids and liquids. Depolarization factors are given for some 30 materials, including commonly used experimental media. The asymmetry coefficient α for the angular distribution of positrons emitted by muons from positive pions at rest is found to be 0.303 ± 0.048.

I. INTRODUCTION

ONE of the experiments which demonstrated nonconservation of parity in the π^+-μ^+-e^+ decay chain also contained the first experimental evidence that polarized positive muons are depolarized on coming to rest inside condensed matter.[1] It was observed that with a given incident beam, the polarization of muons at the time of decay depended critically on the medium in which they decayed. Concurrently it was noted[2] that such a process was to be expected from the behavior of positrons and protons, which are known to attach electrons during the slowing down process and, respectively, form positronium and atomic hydrogen. One might therefore expect that positive muons would form muonium while stopping and depolarize either by the hyperfine interaction or by precession of the muonium in fields known to exist in condensed matter.

While the above observations showed the existence of muon depolarization and suggested a physical basis for the process, one still needed accurate measurements of depolarization in many substances for the following purposes: (a) to serve as a basis for a theoretical understanding of the depolarization process; (b) to normalize measurements in which polarized muons are stopped in scintillators, nuclear emulsions, and bubble chambers; (c) to select media in which muonium or other muon "compounds" may be formed; and (d) to determine the fundamental decay asymmetry for muons produced by pions decaying at rest, since this experiment must necessarily be done inside matter.

The present investigation was undertaken with these aims in view. The following two sections describe the method and results of our measurements on muon depolarization; in Sec. IV these data are applied to the above problems. Most of our results have already appeared in preliminary form.[3]

II. EXPERIMENTAL PROCEDURE

A. Description of Method

Parity nonconservation in the usual production and decay processes of the muon provides a convenient source of longitudinally polarized muons and an equally convenient means of detecting this polarization. The positive muons used in this experiment originate from the decay of pions near the cyclotron target and are extracted in a manner similar to that usually used for pions.[4] Presumably because we do not observe the muon decay in the rest frame of the pion which produces it, our muon beam has about 70% of the longitudinal polarization exhibited by muons from pions which decay at rest. We estimate this figure by comparing the angular distribution of decay positrons resulting from complete π^+-μ^+-e^+ decays in nuclear emulsion[5] with the analogous distribution produced by our beam muons in the same material. (See IV for details.)

The polarized muon beam is stopped in a target of the material being studied, and the relative polarization at decay is derived from the asymmetry parameter[6] a in the positron angular distribution

$$W(\theta)=(1/4\pi)(1-a\cos\theta), \tag{1}$$

where θ is the angle between positron direction and the polarization axis. As was observed in reference 1, the angular distribution can be measured by using a fixed counter and a precessing muon. Consider the distribution, in time and in a plane containing the polarization axis, of positrons emitted after a muon stops

$$N(\phi,t)=(1/2\pi\tau)e^{-t/\tau}(1-a\cos\phi), \tag{2}$$

where τ is the muon mean life, t is time between muon stop and positron emission, and ϕ is an azimuthal

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

† Based on a thesis submitted to the Faculty of the Department of Physics, the University of Chicago, in partial fulfillment of the requirements for the Ph.D. degree.

‡ National Science Foundation Fellow, 1956–1957.

[1] Garwin, Lederman, and Weinrich, Phys. Rev. **105**, 1415 (1957).

[2] J. I. Friedman and V. L. Telegdi, Phys. Rev. **105**, 1681 (1957); and **106**, 1290 (1957). L. Landau [Nuclear Phys. **3**, 127 (1957)] had anticipated this process.

[3] V. L. Telegdi, post-deadline paper, January, 1957 Meeting of the American Physical Society; S. C. Wright, *Proceedings of the Seventh Annual Rochester Conference on High-Energy Nuclear Physics* (Interscience Publishers, Inc., New York, 1957); Swanson, Campbell, Garwin, Sens, Telegdi, Wright, and Yovanovitch, Bull. Am. Phys. Soc. Ser. II, **2**, 205 (1957).

[4] N. P. Campbell and R. A. Swanson (to be published).

[5] A. Weissenberg and V. Smirnitsky, Nuclear Phys. **5**, 33 (1958), give a collection of recent emulsion experiments.

[6] In this paper a denotes the asymmetry for beam muons decaying in a target. It is the product of α, the asymmetry for positrons from muons produced by pions at rest; P, the polarization of beam muons relative to that of muons from pions decaying at rest; and R, the depolarization factor (ratio of muon polarization after stopping to that before stopping). All asymmetries quoted are for the integrated positron energy spectrum.

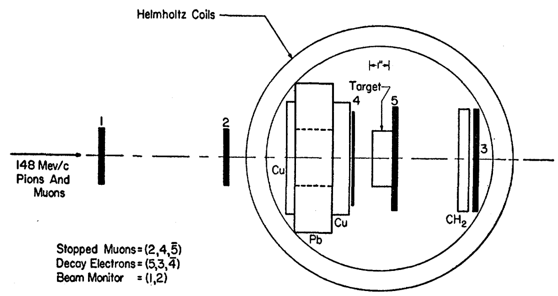

FIG. 1. Experimental arrangement for precession experiments.

angle measured from the polarization axis. A magnetic field B applied perpendicular to the plane causes the muon spin to precess with angular frequency $\omega = geB/2mc$ and results in a distribution

$$N_B(\phi,t) = (1/2\pi\tau)e^{-t/\tau}[1 - a\cos(\phi - \omega t)]. \quad (3)$$

If, as in the arrangement used in the present experiment, $\phi = 0$, one has

$$N_B(0,t) = (e^{-t/\tau}/2\pi\tau)(1 - a\cos\omega t). \quad (4)$$

In the experiments of Garwin *et al.*,[1,7] the positron counter is gated on for an interval Δt at a fixed time t_1, and the asymmetry is observed by varying ω. This very ingenious procedure eliminates the spurious angular dependence due to nonisotropic absorption in the target and simultaneously yields the muon gyromagnetic ratio. One notes, however, that it is statistically inefficient because it ignores information from muon decays occurring at times outside the interval Δt, and because it averages the distribution over an angular interval $\omega\Delta t$ with a resultant reduction of the asymmetry by a factor $(2/\omega\Delta t)\sin(\omega\Delta t/2)$.

We have developed a method for measuring angular distributions by precession which has all the advantages of the preceding method and which gives maximum statistical information for a given counter geometry. If one fixes ω in Eq. (4), the measurement of angular distribution is evidently reduced to the measurement of a time distribution. This is easily done with existing electronic time-measuring circuits which are accurate and reliable in this range. The method uses all muon decays whose positrons enter the counter; one can detect spurious time dependence such as spin relaxation (damping of a with time) or shifts in ω due to internal fields; fluctuations of counter efficiency do not affect the measured distribution; accidentals are measured simultaneously with each run.[8]

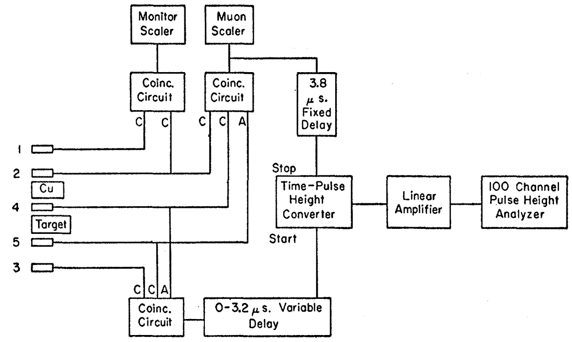

FIG. 2. Block diagram of electronics.

B. Equipment

The experimental arrangement used is shown diagrammatically in Fig. 1. Counters 1–5 are square plastic scintillators viewed by 6810 photomultipliers and are centered on the axis of a 148-Mev/c meson beam (81% pions, 18% muons, and 1% positrons). The beam is moderated by enough copper (29.3 g/cm^2) to stop the pions; the muons stop in the target where they undergo possible depolarization, precession in the applied magnetic field, and decay. The target used is about 60 cm^2 and 5 g/cm^2 thick; it is placed on the axis of a Helmholtz coil and occupies a volume in which the magnetic field is 50.0±0.5 gauss. The stray fields of the cyclotron and focusing magnets are cancelled by compensating coils. Counters 1 and 2 monitor the incident beam. Counters 2, 4, and 5 form a telescope which counts muons incident on, and stopping in, the target. Counters 3, 5, and 4 form a telescope which counts positrons emerging from the target, but rejects particles which do not originate in the target.

Figure 2 is a block diagram of the electronics used to measure the time delay between pulses in the muon and electron telescopes. The coincidence-anticoincidence selection for the muon and electron telescopes is made by conventional coincidence circuits[9] of about 15 mμsec resolving time, and with an anticoincidence efficiency greater than 99.9%. The coincidence-anticoincidence functions of the counters are labeled by the C and A in Fig. 2. The coincidence circuit outputs are fed through suitable delay lines into a time delay to pulse height converter (time converter). The natural time ordering of the muon and positron pulses is inverted by the delay line following the muon telescope in order to start the time converter with the physically later positron pulse. If the time converter were triggered from muons, 90% of the events would have no correlated positron pulse, and hence would give no pertinent information. The pulse-height analyzer dead time (about 400 μsec) would only permit analysis of the first muon in each cyclotron pulse, resulting in the loss of some 70% of the available events. By triggering from

[7] Berley, Coffin, Garwin, Lederman, and Weinrich, Bull. Am. Phys. Soc. Ser. II, 2, 204 (1957).

[8] This method has been used independently by Cassels, O'Keeffe, Rigby, Wetherell, and Wormald, Proc. Phys. Soc. (London) **A70**, 543 (1957).

[9] R. L. Garwin, Rev. Sci. Instr. **24**, 618 (1953).

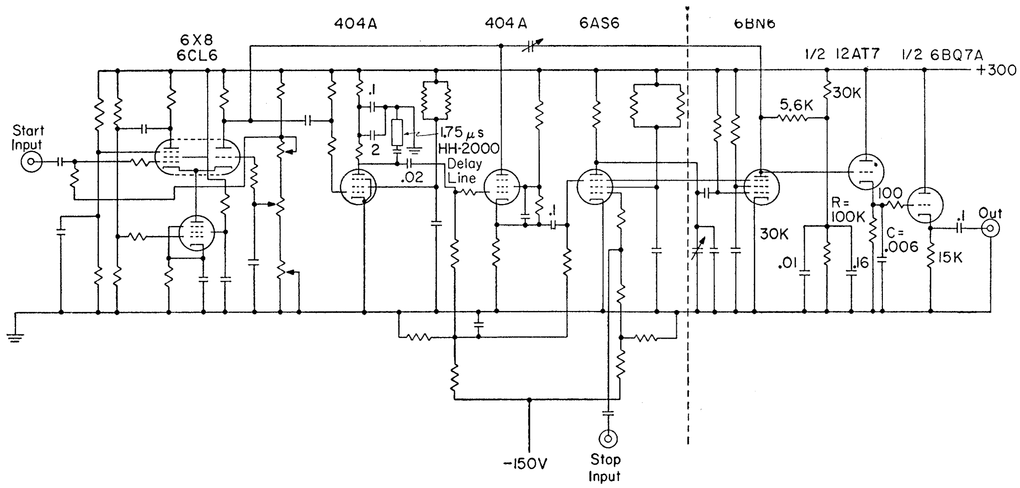

FIG. 3. Time converter schematic diagram. All values not stated are as in reference 10. Major modifications are to right of dotted line.

positrons, the time converter has to handle far less than one event per cyclotron pulse, and dead time losses are less than 10%. The precision variable delay line following the electron telescope is used for calibration purposes; during actual runs it is set to zero delay.

The time converter used here is a modification of a circuit originally developed by Weber *et al.*[10] for neutron time-of-flight measurements, and is shown in Fig. 3. Our circuit differs from that of reference 10 in time range and in the method used to perform the time to amplitude conversion. The modified circuit has a linear range of 3.2 microseconds; its recovery time constant of about 5 microseconds makes it especially suitable for the high instantaneous counting rates encountered with pulsed accelerators. Our modifications stem from the fact that the time conversion system of reference 10, while well suited to the shorter (0.27 μsec) times measured there, was found to have an unusably long recovery time constant (600 μsec) and noticeable (2%) instability when used at 3.2 microseconds. These effects originate respectively in the 6BN6 plate circuit time constant and in poor stability of the current drawn from the time measuring capacitor.

In our time converter a 600-microsecond *RC* circuit is charged to 150 volts by a cathode follower (1/2 12AT7). The circuitry of reference 10 is used to generate a rectangular negative pulse initiated by an electron telescope count (start pulse) and terminated either by a muon telescope count (stop pulse) or after a duration of 3.5 microseconds. This pulse cuts off the cathode follower and thus allows the *RC* circuit to decay for a time equal to the length of the delay being measured. At the end of the delay time, the *RC* is rapidly recharged by the cathode follower with a time constant $T=C/g_m \cong 5$ microseconds. The stability and linearity are determined primarily by the regulated 150-volt dc supply and the *RC* circuit.

[10] Weber, Johnstone, and Cranberg, Rev. Sci. Instr. **27**, 166 (1956).

After linear amplification, the time converter output is analyzed and stored in a 100-channel pulse-height analyzer (Penco PA-3).

C. Equipment Checks

In order to have confidence in the data which follow, various tests of equipment operation were carried out. The counter telescope efficiencies were found to be equal (±2%) and to have no feedthroughs and negligible accidental coincidences. The anticoincidence efficiency was more than 99.9% in both telescopes. As a result, removal of the target reduced the positron rate to about 1% of the "target in" rate.

Calibration of the time converter was carried out as follows. Coincident pulses were produced in both muon and positron telescopes by removing the anticoincidence inputs and allowing mesons to traverse all five counters. The positron pulse was then delayed artificially by the variable delay line to give a calibration curve as shown in Fig. 4. One should note that this is the over-all linearity of time converter, linear amplifier, and pulse-height analyzer measured at the same counting rates as were used in the experiment. The delay line was independently calibrated by resonating it as a half-wave line and measuring the resonant frequency. The linearity and absolute time calibration were thus determined to better than 1%. The stability of repeated calibrations was about ±0.6%.

To test the over-all operation, we have verified the sign of the muon *g* factor by displacing the positron telescope through a known angle and observing the shift in the time distribution; we have measured the magnitude of *g* to be 1.987±0.034. We find the muon mean life to be $\tau = (2.20\pm0.06)\times10^{-6}$ sec; our accuracy here is limited because we observe only 1.5 lifetimes.[11] On stopping pions in a nondepolarizing target (graph-

[11] On extending the range we have obtained $(2.21\pm0.02)\times10^{-6}$ sec. See Sens, Swanson, Telegdi, and Yovanovitch, Phys. Rev. **107**, 1464 (1957).

ite), we observe the isotropic distribution of decay positrons expected because of the isotropic emission of muons.

In a typical one-hour run we had 1.5×10^7 monitor counts, 10^6 stopped muons, and 4×10^4 decay positrons. This is sufficient to give a statistical accuracy of ±0.01 for a.

III. DATA ANALYSIS

The muon decay asymmetries were calculated from the time-converter pulse-height distributions by the following procedure. The data from each run were grouped into 13 intervals, each 5 channels wide, labeled by an index n. After grouping, the data were fitted by a weighted least squares procedure to a distribution function.

$$F(n)=e^{Nn}(Ae^{-\lambda n}-Be^{-\lambda n}\cos\nu n+C), \tag{5}$$

where λ is the muon decay rate, ν is the precession frequency, and N is the instantaneous stop rate (muon pulse rate). The fit was made for the parameters A, B, and C; B/A is essentially the decay asymmetry, and C represents background from accidental events. The excellent stability of the time converter and the magnetic field permitted the use of a common muon decay rate and precession frequency for all runs. λ was calculated from the muon lifetime (2.22 ± 0.02 μsec)[12] and the mean time calibration $n=(5.34\pm0.03)t-(2.36\pm0.08)$, where t is in microseconds. ν was obtained by least-squares fitting of the frequency of three graphite runs which gave $\nu=0.790\pm0.009$. N is the instantaneous muon stop rate, obtained by making an accidentals measurement for each run. The combined accidentals from all runs were used to calculate a ratio F of instantaneous/average muon stop rate. The value of N is then the average muon stop rate during a run multiplied by this factor F. Because of the labor involved in these calculations, we have developed a code for the IBM-650 computer which calculates A, B, C, B/A, error in B/A, and χ^2. A single fit is done in about 20 seconds.

The distribution function $F(n)$ is justified in Appendix I, where it is shown that the factor e^{Nn} results directly from the presence of uncorrelated stop pulses and the fact that a time converter measures the time distribution of only the first stop pulse following a start pulse.

The ratio B/A obtained from the least-squares analysis is not the asymmetry a of the positron angular distribution. The following correction factors must be considered.

1. Time Averaging

The data were grouped into 13 intervals of angular width $\eta=0.790$ radian. It is easily shown that such grouping diminishes the asymmetry by a factor $f_1=(2/\eta)\sin(\eta/2)=0.974$.

[12] W. E. Bell and E. P. Hinks, Phys. Rev. **84**, 1243 (1951).

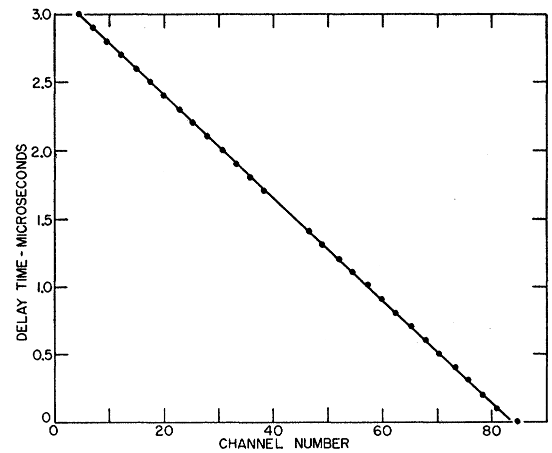

FIG. 4. Typical time converter calibration curve.

2. Muon Stop Rate

As shown in Appendix I, the presence of an uncorrelated stop rate N in the time converter enhances the asymmetry by a factor $f_2=1/(1-Nt)\cong1.1$.

3. Counter Geometry

The finite positron counter and target sizes diminish the measured asymmetry by averaging the positron angular distribution. As the geometry of our experiment is not amenable to analytic treatment, a calculation of solid angles and mean values of $\cos\theta$ was done numerically for each of our targets. As anticipated, the resultant geometrical correction factor, f_3, is not sensitive to the target used. For all targets used, f_3 is about 0.91 ± 0.01. Measurements on graphite targets in improved geometry ($f_3=0.975$) agree with those in the geometry of Fig. 1.

4. Positron Energy Loss and Scattering

We have deliberately chosen thin, low Z targets in order to minimize the effects of interaction of the decay positrons with the target material. An estimate of this effect using the two-component neutrino decay spectrum,[13] Monte Carlo calculations of electron straggling,[14] and recent measurements of electron multiple scattering[15] shows that the asymmetry is increased by about 2% for our 4.4-g/cm^2 graphite target. Measurements with magnesium targets of 4.9 and 9.8 g/cm^2 and graphite targets of 4.4 and 8.8 g/cm^2 show that this effect is indeed less than our statistical errors ($\pm4\%$). We therefore assume that the asymmetry parameter observed for all targets is increased by a factor $f_4=1.03\pm0.02$.

The effects of pions stopping in the target and of decays occurring outside the target were found to be

[13] C. N. Yang and T. D. Lee, Phys. Rev. **105**, 1671 (1957).
[14] Leiss, Penner, and Robinson, Phys. Rev. **107**, 1544 (1957).
[15] Hanson, Lanzl, Lyman, and Scott, Phys. Rev. **84**, 634 (1951).

TABLE I. Decay asymmetries and depolarization factors for positive muons.

Target	a	$\pm\delta a$	R
Graphite I[a]	0.236	0.011	1.00
II	0.220	0.012	
III	0.237	0.010	
IV	0.243	0.011	
V[b]	0.227	0.012	
VI[c]	0.210	0.012	
VII[c]	0.233	0.016	
Lampblack	0.253	0.021	1.10
Diamond	0.045	0.008	0.20
Al	0.209	0.010	0.91
Be	0.222	0.012	0.97
Li	0.201	0.014	0.88
Mg I[d]	0.223	0.013	1.04
Mg II	0.254	0.013	
Si	0.253	0.012	1.10
SiC	0.213	0.011	0.93
B_4C[e]	0.23	0.02	1.00
Al_2O_3	0.022	0.009	0.10
Fused SiO_2	0.038	0.009	0.17
Vitreosil	0.038	0.008	0.17
Crystalline SiO_2[f]	0.01	0.02	0.04
Silicone DC-200	0.139	0.010	0.61
Water p_H 6.5[g]	0.141	0.011	0.62
NaOH p_H 12	0.131	0.012	
HCl p_H 2	0.121	0.011	
p_H 1.2[h]	0.158	0.011	
p_H 2.2	0.141	0.011	
p_H 4.4	0.139	0.011	
p_H 5.3	0.149	0.011	
p_H 6.1	0.142	0.011	
p_H 6.2	0.151	0.012	
p_H 7.0	0.134	0.011	
p_H 9.5	0.167	0.013	
p_H 11.0	0.144	0.011	
p_H 11.2	0.141	0.011	
Polyethylene	0.146	0.012	0.64
Polystyrene[i]	0.070	0.010	0.31
Propane[j]	0.170	0.020	0.74
Benzene	0.046	0.012	0.21
Phenylcyclohexane[k]	0.084	0.011	0.37
Chloroform	0.184	0.015	0.80
Chloroform+DPH[l]	0.233	0.014	1.02
P	0.025	0.017	0.11
S	0.014	0.011	0.06
CsI	0.031	0.013	0.14
NaCl	0.041	0.009	0.18
MgF_2	0.136	0.009	0.59
MgO	0.079	0.012	0.35
Nuclear emulsion I[m]	0.092	0.011	0.38
II	0.073	0.010	
III	0.095	0.011	
IV[n]	0.145	0.034	

[a] Graphite mean $=0.229\pm0.008$.
[b] 8.8-g/cm² target. All other graphite 4.4 g/cm².
[c] Good geometry run ($f_3=0.975$).
[d] 9.8-g/cm² target. Mg II is 4.9 g/cm².
[e] Precesses with spin relaxation. This is initial asymmetry in 100 gauss.
[f] 88 gauss.
[g] Mean for all aqueous solutions $=0.143\pm0.008$.
[h] Variable p_H runs were 0.07 NaCl to stabilize Na^+ and Cl^- concentration. p_H was varied by adding HCl or NaOH.
[i] Plastic scintillator.
[j] Liquid at $-80°C$.
[k] Liquid scintillator.
[l] 2 g/l diphenylhydrazine added.
[m] Emulsion mean $=0.087\pm0.009$.
[n] 13 g sample. See text.

negligible. We have in addition considered the effects of uncertainties in time calibration, muon stop rate, precession phase, and magnetic field on the observed asymmetries; these causes contribute jointly an error of 1.2% in a.

The decay asymmetries observed in this experiment are collected in Table I. The values indicated in the column labeled a were obtained by taking the ratio B/A of the least squares fit to the time converter data and dividing by the four correction factors listed above. The error listed, δa, is that computed from statistics and the errors of counter geometry, positron loss, and the timing and phase error. If one considers substances which have been measured several times (graphite, aqueous solutions, and nuclear emulsions) it is evident that the observed standard deviation is of the same magnitude as the computed error.

IV. DISCUSSION OF DATA

In order to express the asymmetries in Table I as depolarization factors, we make use of an experiment which establishes the absolute depolarization of one of our targets. It has been shown[16] that the muon spin can be decoupled from depolarizing angular momenta by an external axial magnetic field. We note in particular that a field of 7 kilogauss inhibits 70% of the depolarization of muons in nuclear emulsion and in vitreosil (fused quartz), but produces no change in polarization for graphite targets. We conclude from these data that the depolarization factor R for graphite is 1.00 ± 0.06; the error is computed from counting statistics and counter geometry. The depolarization factors R in Table I are then calculated as the ratio of an observed a to the mean a for graphite.

A. Depolarization Mechanism

It is evident that substances in Table I which are good electronic conductors depolarize little or not at all; insulators and ionic conductors are found to give partial depolarization in all cases. This suggests a behavior similar to that of positrons in solids[17]; screening due to conduction electrons can prevent spin interactions with electrons in metals, while the binding of electrons in insulators would permit the existence of coupled systems if once formed. An exception seems to arise when the free radical diphenylhydrazine is added

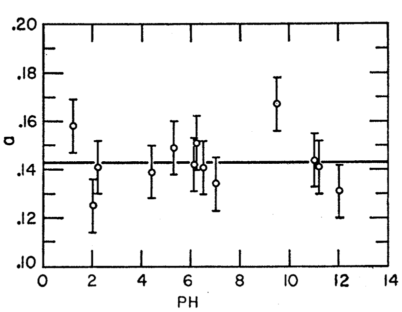

FIG. 5. Asymmetry of muon decay in aqueous solutions of variable p_H.

[16] Sens, Swanson, Telegdi, and Yovanovitch, Phys. Rev. **107**, 1465 (1957).
[17] R. A. Ferrell, Revs. Modern Phys. **28**, 308 (1956).

to chloroform; the depolarization is completely inhibited. The results of our runs in aqueous solutions of variable p_H are summarized in Fig. 5, from which it is apparent that no observable effect exists.[18]

The most interesting information is found in the precession curves (Fig. 6 is a typical graphite run after decay correction), where we find that in all cases but one the precession amplitude is constant in time. This implies that the depolarization is rapid ($<10^{-7}$ sec) for those muons affected, while the remainder are unperturbed in the 3 microseconds of observation. Depolarization must therefore be caused by a relatively strong paramagnetic interaction such as in muonium and not by the weak fields which produce relaxation of nuclear spins. Our factor R is evidently the probability that a muon is slowed to thermal velocities without depolarization, since thermal muons are clearly not depolarized in most materials. The one exception is B_4C (see Fig. 7) which shows maximum asymmetry ($a=0.23$) at $t=0$ and then exhibits spin relaxation with a mean life of 6.5 microseconds.

B. Normalization of Techniques

Table I contains measurements on liquid and plastic scintillators, nuclear emulsions, and liquid propane. Evidently propane bubble chambers are well suited for investigating polarized muons.[19] Emulsion sample IV is of interest because it is from the same emulsion batch as was used by Lattes *et al.*[20] to observe cosmic-ray π-μ-e decays. Our result shows that the observed low asymmetry was not due to depolarization in the emulsion.

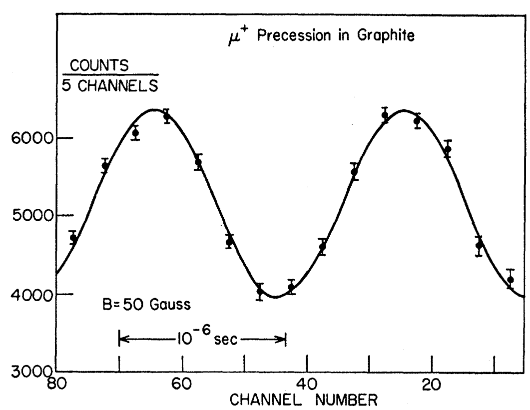

FIG. 6. Muon precession in graphite after decay and background correction.

[18] The measurements on aqueous solutions were motivated by theoretical speculation and unpublished data from another laboratory which indicated that a p_H dependence could and did exist.

[19] Liquid hydrogen is probably even better. See Abashian, Adair, Cool, Erwin, Kopp, Leipuner, Morris, Rahm, Rau, Thorndike, and Whittemore, Phys. Rev. **105**, 1927 (1957).

[20] Lattes, Fowler, Freier, Ney, and St. Lorant, Bull. Am. Phys. Soc. Ser. II, **2**, 206 (1957).

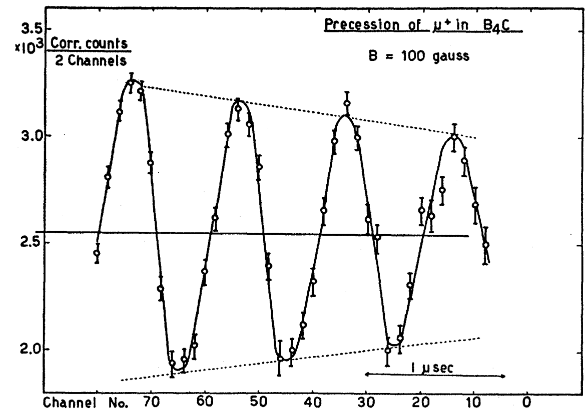

FIG. 7. Muon precession in boron carbide after decay and background correction.

C. Muonium

Our depolarization measurements in silicone liquid, fused quartz, and crystalline quartz were motivated by our knowledge of positronium formation in these substances.[21] The observed depolarization is consistent with a model of muonium formation, which can only result in a depolarized state or a triplet 1S state whose g factor is one hundred times that of the free muon. The presence of polarized triplet muonium can therefore be observed in our equipment by precessing the muonium in a field one hundred times lower than that used for muon precession. Precession experiments with fused quartz, silicone liquid, and Teflon in a field of 0.4 gauss showed the precession amplitude to be $0\pm8\%$ of that found for muons in graphite at 50 gauss.[22] We conclude that polarized muonium either is not formed or is rapidly depolarized in solids.

D. Decay Asymmetry of Muons from Pions at Rest

The decay of muons from pions at rest has been observed in hydrogen[19] and propane[23] bubble chambers and in nuclear track plates.[2,5,24] As observed in reference 2 and by Wilkinson,[24] these data can be used to determine the free π-μ-e asymmetry α if one can determine the depolarization undergone by the muon before decay. Wilkinson's calculation was made from preliminary asymmetry data on emulsion and graphite and by assuming no depolarization in graphite, since the result of reference 16 was not available. We now have all the data necessary for this calculation. From reference 16,

[21] Positronium is not expected to be a good analog because of the markedly different energies of muon and positron at the Bohr velocity, where electron capture is most probable. As an example, fused and crystalline quartz depolarize muons equally but only fused quartz exhibits triplet positronium.

[22] Campbell, Garwin, Sens, Swanson, Telegdi, Wright, and Yovanovitch, Bull. Am. Phys. Soc. Ser. II, **2**, 205 (1957).

[23] Pless, Brenner, Williams, Bizzarri, Hildebrand, Milburn, Shapiro, Strauch, Street, and Young, Phys. Rev. **108**, 159 (1957).

[24] D. H. Wilkinson, Nuovo cimento **6**, 516 (1957) gives a compilation of nuclear emulsion data; see also reference 5.

the graphite depolarization factor R is 1.00 ± 0.06. The residual polarizations or emulsion and propane relative to graphite are 0.380 ± 0.037 and 0.742 ± 0.091 (Table I). The π-μ-e asymmetries in emulsion and propane are 0.127 ± 0.017 and 0.18 ± 0.05. A simple calculation gives $\alpha=0.334\pm0.059$ for emulsion and $\alpha=0.243\pm0.075$ for propane. The weighted mean is $\alpha=0.303\pm0.048$. This result is consistent with the prediction $\alpha=\frac{1}{3}$ given by the two component muon decay theories[25] with $|V/A|=1$ interaction.

E. Beam Polarization

The decay asymmetry observed for our beam muons stopping in nuclear emulsion is 0.087 ± 0.009. The asymmetry of muons from pions decaying at rest in nuclear emulsion is 0.127 ± 0.017.[5] Since depolarization by the absorber is negligible,[26] the ratio of asymmetries must be the ratio of muon polarizations. We thus find 0.68 ± 0.17 as the polarization of our beam relative to the polarization of muons from pions at rest.

V. ACKNOWLEDGMENTS

I am indebted to Professor V. L. Telegdi for suggesting this investigation and for constant encouragement and advice. I wish to thank J. C. Sens and D. D. Yovanovitch for aid in making the measurements, K. H. Benford for time converter modifications, and E. Silverstein for assistance in computer coding.

APPENDIX I. BACKGROUND EFFECTS IN TIME CONVERTERS

Consider a time converter of the type described here which receives correlated start and stop pulses with a time distribution[27] $\delta(t-\alpha)$ in the presence of uncorrelated stop pulses with rate N. The time distribution measured by the converter will be

$$f(t,\alpha)=Ne^{-Nt}+e^{-N\alpha}\delta(t-\alpha) \quad \text{for} \quad 0\leq t\leq\alpha, \tag{6}$$

$$=0 \quad \text{for} \quad \alpha\leq t, \tag{7}$$

corresponding to the fact that the converter can receive an uncorrelated stop pulse in the interval $0\leq t\leq\alpha$. For an arbitrary distribution given by

$$g(t)=\int_0^\infty g(\alpha)\delta(t-\alpha)d\alpha, \tag{8}$$

the time distribution measured by the converter will be the corresponding integral of $f(t,\alpha)$.

$$F[t,g]=\int_t^\infty g(\alpha)d\alpha\, Ne^{-Nt}+g(t)e^{-Nt}. \tag{9}$$

In our experiment, $g(t)=e^{-t/\tau}(1-a\cos\omega t)$. Integration gives

$$F(t)=e^{-Nt}\bigg[e^{-t/\tau}(1-a\cos\omega t) +N\tau e^{-t/\tau}\bigg(1-\frac{a}{1+\omega^2\tau^2}\cos\omega t+\frac{a\omega\tau}{1+\omega^2\tau^2}\sin\omega\tau\bigg)\bigg]. \tag{10}$$

For our values of N, λ, and ω one can approximate

$$F(t)=e^{-(N+1/\tau)t}(1+N\tau-a\cos\omega t). \tag{11}$$

When the time converter is used inverted, i.e., triggered by the physically later positron pulse, a similar analysis yields

$$F(t)=e^{-NB+Nt}[e^{-t/\tau}(1-N\tau-a\cos\omega t) +N\tau(1+e^{-B/\tau})], \tag{12}$$

where B is the delay used to invert pulse order. The corrections derived above are quite important (about 10%) for this work and for measurements of lifetimes using time converters.

---

[25] R. P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958).
[26] S. Hayakawa, Phys. Rev. **108**, 1533 (1957).
[27] Dirac δ function.