upper hemisphere. A positive result to this experiment would be evidence both for the existence of an intermediary boson and for the absence of a selection rule that prevents those neutrinos produced in association with muons from interacting with electrons.

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Magnetic Quenching of Hyperfine Depolarization of Positive Muons*

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The depolarization of positive muons being slowed down in an insulating material can only be accounted for by the capture of an electron into a bound state. The ground-state muonium formed in flight can be expected to break up in a time short compared to 10^{-10} sec (the time necessary for the electron to flip the muon spin via the hyperfine interaction). The effect of an external magnetic field in locking the electron spin in its initial orientation, and thereby quenching the action of the hyperfine coupling, is a useful test of the assumption of muonium as the depolarizing mechanism. If x is the magnetic field strength measured in units of 1.58 kilogauss, and τ is twice the mean life of the muonium atoms with respect to breakup, measured in units of 3.58×10^{-11} sec, then it is found that the amount of depolarization for one formation and breakup process is equal to one-half of the quantity $(1+\tau^{-2}+x^2)^{-1}$. By introducing n, the number of times that the capture-breakup process is repeated, one has two parameters and can achieve good fits to the experimental data of Sens et al. for nuclear emulsion and fused quartz. It is pointed out that the interpretation by Sens et al. of their magnetic quenching data, also based on a two-parameter formula, is not tenable, since it depends on assuming that a certain fraction of the muons are not subject to the capture and loss process.

It is known that when a fast positive muon enters condensed matter, in many substances it loses some or all of its initial polarization in the slowing down process. To account for this depolarization, it is necessary to invoke the spin-spin interaction of the magnetic moments of the muon with the electrons in the matter, as there is not available any other sufficiently strong interaction to give the observed effect.[1] In addition to this requirement, it is necessary that the muon not be exposed in rapid succession to many different electrons with random spin orientation, as this would average out the effect and give essentially no depolarization. Thus it is necessary that the muon capture an electron and form a muonium atom. It is only in this way that it may be exposed to just one electron of a definite spin orientation for a sufficiently long period of time to result in a secular precession of the spin of the muon. This requirement is consistent with the fact that metals do not exhibit the depolarization of muons, while insulators generally do. Thus, in metals the muon is always exposed to a random distribution of conduction electrons and does not accumulate any secular precession leading to a loss in its spin orientation. In addition to the requirement that the muon should capture an electron and form the muonium atom it is necessary that the atom should be in the ground state, as the excited states have too weak a hyperfine interaction to give sufficient depolarization.

In testing any such depolarization mechanism as muonium, it is very useful to apply a laboratory magnetic field, and to study the dependence of the depolarization mechanism on the strength of the field. Since the flipping of the muon spin in the muonium atom is accompanied by a recoil flip of the electron spin, as required by conservation of angular momentum, it is clear that the depolarization mechanism can be controlled by having the electron be acted upon by the external magnetic field. Thus, if the field is made strong enough, the electron can be locked in its initial orientation by the Paschen-Back effect. The muon spin is then locked into position by a kind of indirect Paschen-Back effect. (The direct action of the external field on the muon is negligible compared to this indirect effect through the electron.) The simplest possible theoretical treatment which satisfies the requirements of the preceding paragraph is that of "one-time" muonium formation. In this picture a fast muon enters a solid material, is very quickly stopped, and then captures an electron, which subsequently remains bound to the muon until the latter decays. The effect of an external magnetic field on such a simple depolarization process has been studied by Breit and Hughes[2] and by Ferrell and Chaos.[3] It has been shown by Orear, Harris, and Bierman,[4] and also in reference

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[1] Here we include the magnetic quenching effect discussed below. Hyperfine interaction with nuclei would be quenched much more easily than is found to be the case.

[2] G. Breit and V. W. Hughes, Phys. Rev. **106**, 1293 (1957).
[3] R. A. Ferrell and F. Chaos, Phys. Rev. **107**, 1322 (1957).
[4] J. Orear, G. Harris, and E. Bierman, Phys. Rev. **107**, 322 (1957).

3, that the dependence of the polarization on the magnetic field in this simple model is given by

$$P=\frac{1}{2}+\frac{1}{2}\frac{x^2}{1+x^2}. \tag{1}$$

Throughout the present paper, we will use the notation of reference 3. x is the magnetic field measured in units of 1.58 kilogauss. The dependence of this polarization on magnetic field is plotted in Fig. 1 of reference 3 and it will be noted that a cross-over occurs at about $x=1$, or at about 1.5 kilogauss. Fields significantly larger than this value will restore the polarization lost because of the hyperfine interaction between the muon and the electron. This simple theory has been tested qualitatively by Orear et al.,[4] and by Barkas et al.,[5] who verify that the polarization is completely restored in large magnetic fields of the order of 10 kilogauss. But the more detailed investigation of Sens et al.[6] showed that the depolarization persists up to fields of the order of 4.5 kilogauss or $x=3$. At this field about one-half of the depolarization was found to be restored or "quenched." It is clear that this behavior cannot be explained in terms of one-time muonium formation [Eq. (1)]. For this reason Sens et al.[6] proposed the following equation based on the idea that a fraction f of the muons undergoes n repeated capture and loss processes, and the fraction $1-f$ remains immune and does not ever capture electrons in the course of being slowed down:

$$P=1-f+f\left(\frac{1}{2}+\frac{1}{2}\frac{x^2}{1+x^2}\right)^n. \tag{2}$$

But this explanation is not tenable, as there is no reason to expect that the muons will divide up into two groups in this way and be subjected to different treatments by the medium. The purpose of this note is to propose a different modification of the simple one-time muonium depolarization mechanism, and to derive an alternative formula which will replace Eq. (2). The new formula will be equally successful in explaining the data, and will be better founded in the basic physical principles.

Since the events involved in the slowing down process are generally regarded as being fast, occurring in time of the order of magnitude of only 10^{-11} sec, while the time required for an electron in the muonium ground state to flip the muon spin is 10^{-10} sec, it is clearly necessary to take account of the finite lifetime of the muonium atom with respect to breakup. Equations (1) and (2) above are based on the assumption that the muonium lives indefinitely, or at least for a time long compared to 10^{-10} sec. They are therefore, clearly not to be regarded as reliable for the actual slowing down process that is taking place in the condensed material. It is, however, a simple matter to modify the theory of reference 3 to take account of breakup of the muonium for times of the same order or shorter than the hyperfine depolarization time. It is convenient to introduce the unit of time 3.58×10^{-11} sec, which is $(2\pi)^{-1}$ times the reciprocal of the hyperfine period. If we now consider that we cause a muon to capture an electron at time zero, then the residual polarization of the muon at time t measured in the above unit, and averaged over initial electron spin orientation is given by

$$\langle\sigma_\mu{}^H\rangle=1-\frac{\sin^2(1+x^2)^{\frac{1}{2}}t}{1+x^2}\rightarrow 1-\frac{\sin^2[(1+x^2)^{\frac{1}{2}}(t/2)]}{1+x^2}. \tag{3}$$

Since we are interested in the statistical problem of averaging over the various individual events which occur in the slowing down process, we can introduce $\tau/2\rightarrow\tau$ for the mean life with respect to breakup and weight the polarization given by Eq. (3) by the quantity

$$2/\tau\exp(-2t/\tau)dt\rightarrow\frac{1}{\tau}\exp\left(-\frac{t}{\tau}\right)dt.$$

Carrying out this average, which we denote by the subscript τ, we find

$$\langle\sigma_\mu{}^H\rangle_\tau=1-\frac{1}{2}\frac{1}{1+\tau^{-2}+x^2}. \tag{4}$$

We note that this checks in the limits of $\tau\rightarrow\infty$, in which case it reduces to Eq. (1), and $\tau\rightarrow 0$, in which case there is no depolarization, because there has simply been no time available for it to take place. We further note that for values of τ of the order of unity or less, the field required to quench one-half of the depolarization corresponds to $x>1$. This is already in the direction of giving better agreement with the data of Sens et al.[6]

It is now necessary to take account of the fact that upon breakup, the muon will continue for a while through the medium, ionizing as it goes and being slowed down, but probably eventually again capturing an electron. Thus we will again have muonium, but now with a somewhat longer mean life because of the lower translational velocity. It is easy to establish that the net polarization after several such transitory muonium histories is given simply by the product of factors of the form of Eq. (4). In order to avoid the complications of the slowing down theory, we make here the simple approximation of assuming all the mean lives during the slowing down process to be the same. Although this approximation is dictated by simplicity, it is not unreasonable. In the initial phases of the slowing down process there will occur very many short-lived muonium cases. But as we have seen above, these have a completely negligible depolarizing effect. Toward the end of the slowing down process, after a

[5] W. H. Barkas, P. C. Giles, H. H. Heckman, F. W. Inman, and F. M. Smith, Phys. Rev. 107, 911 (1957).
[6] J. C. Sens, R. A. Swanson, V. L. Telegdi, and D. D. Yovanovitch, Phys. Rev. 107, 1465 (1957).

time of the order of 10^{-11} sec, or perhaps somewhat longer, we can imagine that the muonium breaks up for the last time, since the breakup cross section is generally expected to be much greater than the capture cross section. Thus it is also reasonable not to consider large values of τ. In any case, we assume that the repeated captures and breakups can be represented by some *effective* mean life, and find for the final polarization of the muon at the time that it decays the expression

$$P=\left(1-\frac{1}{2}\frac{1}{1+\tau^{-2}+x^2}\right)^n. \tag{5}$$

This equation replaces Eq. (2) proposed by Sens et al.[6] It also contains two parameters, $\tau/2 \rightarrow \tau$, the effective mean life with respect to breakup, and n, the average number of intermediate muonium formations. A convenient procedure for obtaining a fit to the experimental data is to consider that value of the magnetic field strength, x_m, for which the polarization is equal to the geometrical mean of its value for zero and infinite field strengths. x_m is readily estimated from the experimental data. In terms of x_m, τ is determined by the following equation:

$$\tau=\left[-\tfrac{3}{4}+\left(\tfrac{1}{16}+x_m^4\right)^{\frac{1}{2}}\right]^{-\frac{1}{2}}. \tag{6}$$

n can now be determined from τ and P_0, the zero-field

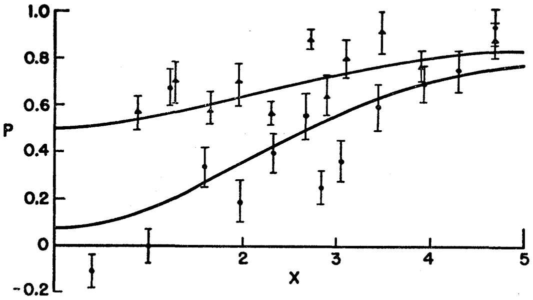

FIG. 1. Dependence of muon polarization P on magnetic field x, measured in units of 1.58 kilogauss. The magnetic quenching data shown are those of Sens et al. (reference 6) for nuclear emulsion (triangles) and fused quartz (circles). The fits achieved by the present theory, which takes into account the finite lifetime of the muonium atom with respect to breakup, are given by the upper and lower curves (nuclear emulsion and fused quartz, respectively).

polarization:

$$n=\frac{\ln P_0}{\ln[1-1/2(\tau^{-2}+1)]}. \tag{7}$$

Figure 1 shows the data of Sens et al.[6] represented by solid triangles for nuclear emulsion and by solid circles for fused quartz. Fits are given to this data by $\tau=0.38$ and $n=10.1$ for nuclear emulsion and by $\tau=0.7$ and $n=13.5$ for fused quartz, and are exhibited by the upper and lower curves, respectively.

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Absorption of Negative Muons in C^{12} Leading to Production of Bound B^{12}*†

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A negative muon beam from the Carnegie Tech synchrocylotron was stopped in a six-inch propane bubble chamber. Since the hydrogen does not form μ-mesonic atoms in the presence of carbon, the pictures yield information on the interaction of stopped muons with carbon. About 30 000 pictures of stopping muons were taken with the bubble chamber kept sensitive for ~20 msec after the beam pulse in order to observe the beta decay of any bound B^{12} nuclei resulting from μ absorption by carbon. The chamber was photographed right after the beam pulse to determine whether a given stopped muon decayed, or was absorbed. Another photograph was taken about 15 msec later to determine if the absorption had led to a nucleus which had beta decayed. A count of μ-e decays in the same film allowed the determination of the probability per unit time of bound B^{12} formation. Forty-six boron decays were observed yielding $(7.6\pm1.2)\times10^3$ sec^{-1} for the rate of bound B^{12} production. Possible interpretation of this result in terms of a universal V-A Fermi interaction is discussed.

INTRODUCTION

THE theory of the universal V-A Fermi interaction[1] leads to a clear cut prediction concerning the rate of the capture process

$$\mu^-+p\rightarrow n+\nu. \tag{1}$$

This theory has been quite successful in explaining the available experimental data, and further verification, in the form of a measurement of the absorption rate

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‡ Now at Princeton University, Princeton, New Jersey.
[1] R. P. Feynman and M. Gell-mann, Phys. Rev. **109**, 193 (1958); E. C. G. Sudarshan and R. E. Marshak, Phys. Rev. **109**, 1860 (1958); J. J. Sakurai, Bull. Am. Phys. Soc. **3**, 10 (1958).