FORMATION OF MUONIUM AND OBSERVATION OF ITS LARMOR PRECESSION*

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After the discovery[1,2] that muons which originate from pion decays are polarized and that positrons which originate from muon decays are emitted with an angular asymmetry with respect to the spin direction of the muons, it was realized[2,3] that it should be possible to observe the atom consisting of a positive muon and an electron (called muonium) and to measure its hyperfine structure. The present Letter reports the formation of muonium in pure argon gas; muonium is observed through its characteristic Larmor precession frequency.

Muonium in its ground $1\,^2S_{1/2}$ state can be formed when a positive muon is slowed down in matter and captures an electron from an atom in the stopping material. If the muons are polarized, the muonium atoms formed should also have a net polarization.[4] Specifically, if the z axis of quantization is taken along the direction of the momentum of the incident muon beam, then the spin direction of a positive muon will be in the negative z direction to a good approximation.[5] Hence substates $(F, m_F) = (1, -1)$, $(1, 0)$, and $(0, 0)$ will form in the relative amounts 1/2, 1/4, and 1/4, respectively, where F is the quantum number for total atomic angular momentum and m_F is the associated magnetic quantum number. In the states $(1, 0)$ and $(0, 0)$ the muon is unpolarized; the time involved in establishing these unpolarized states subsequent to the electron capture by the muon is determined by the hyperfine structure interaction between the electron and the muon and is of the order of 10^{-10} sec. In the state $(F, m_F) = (1, -1)$ the muon is polarized with its spin along the negative z axis.

Many searches have been made for muonium since 1957. Usually[6,7] the attempt has been to observe the characteristic precession frequency of muonium in the state $(F, m_F) = (1, -1)$ in an external magnetic field H whose direction is perpendicular to the direction of the incoming muon beam (or equivalently to the axis of quantization). The muonium spin angular momentum will precess[8] about H with the frequency $f = \mu H/h$ [μ = magnetic moment of the $(1, -1)$ state of muonium], which is 1.39 Mc/sec-gauss. The published accounts indicate that solid or liquid targets have been used. An experiment has also been done[9] to look for a Zeeman transition between the $F = 1$ magnetic sublevels of muonium induced by a radio-frequency field, when muons are stopped in N_2O gas at 50 atm pressure.

A wide variation has been observed in the amount of depolarization of positive muons stopped in different materials.[6,10,11] The polarization is measured in a precession experiment in which the magnetic field is chosen so as to detect the precession of a free muon; in such an experiment polarized muonium would appear unpolarized because of its high precession frequency. The observed variation in polarization has often been ascribed to varying amounts of muonium formation. However, this explanation is not necessarily correct because one can conceive of other depolarizing mechanisms, e. g., those resulting from chemical reactions of the muon.[12]

The present experiment was designed to search for muonium in pure argon gas at high pressure. The argon gas was contained in a stainless steel cylinder at a pressure of 50 atm and was purified by recirculation over titanium sponge heated to 500°C. First the depolarization of the muons stopped in the gas was measured in a free-muon precession experiment.[1] The value of the ratio of the asymmetry parameter, a, for argon to that for carbon was 0.08 ± 0.15, and thus within the accuracy of the experiment no free polarized muons remain in argon. This result is a necessary condition that all the muons form muonium.

As a specific search for muonium, the characteristic precession frequency of muonium in the state $(F, m_F) = (1, -1)$ was looked for in the manner indicated in Fig. 1. An external magnetic field H between 3 and 5 gauss was applied perpendicular both to the direction of the incoming muon beam and to the direction from the target to the positron telescope, and its value was measured to an accuracy of 1% with an electron reso-

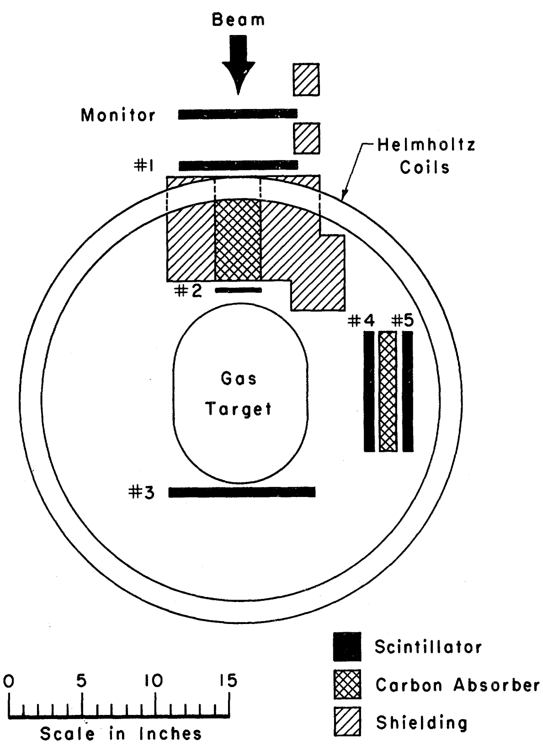

FIG. 1. Experimental arrangement.

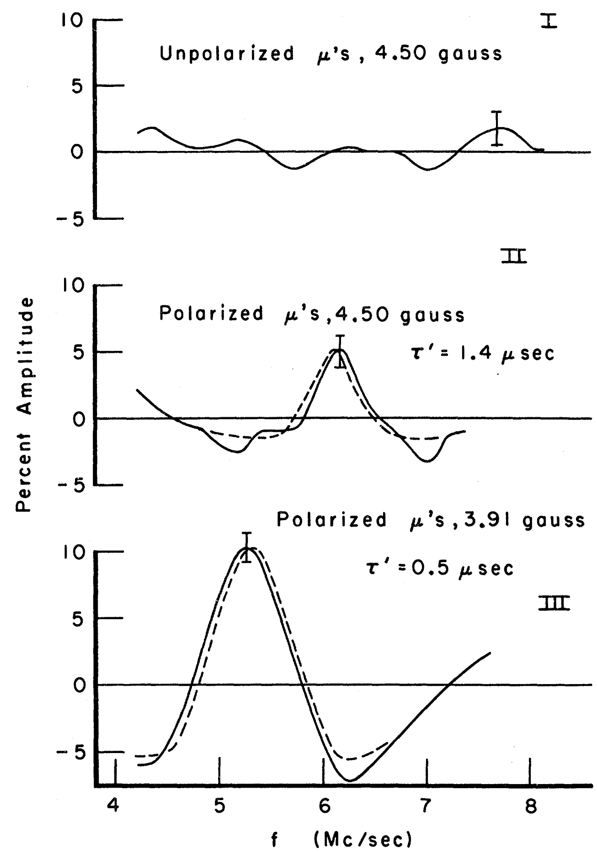

FIG. 2. Frequency analysis.

nance spectrometer using DPH free radicals. The distribution of time intervals between the incoming muon pulses (1-2-$\bar{3}$ coincidences) and those decay positron pulses (4-5 coincidences) which came between 0.2 and 2.0 microseconds after the muon pulse was converted to a spectrum of pulse heights which was fed into a pulse-height analyzer. The characteristic precession of polarized muonium should appear as an oscillation in the pulse-height analyzer data.

The data were assumed to represent the sum of four components, due to (1) polarized muonium, (2) polarized free muons, (3) unpolarized muons, and (4) accidental coincidences. We determined the amplitudes of (2) through (4) by a least squares procedure in which (1), which must be represented by a rapidly varying periodic function, would not contribute. With these computed amplitudes, the contributions of (2) through (4) to the data were then subtracted, leaving numbers y_i containing only the desired oscillation due to polarized muonium. A least squares fit to the y_i was made using the function

$$y_i = e^{-t_i/\tau}\left\{C + Ae^{-t_i/\tau'} \sin[2\pi f(t_i + t_0)]\right\}.$$

Here τ is the muon mean lifetime; τ' is a parameter introduced in order to allow for line broadening, either through field inhomogeneities, drifts in electronics, or depolarization of muonium in collisions; f is the trial value for the precession frequency of the magnetic moment of muonium; t_0 is the time delay between the stopping of the muons and the emission of the earliest positrons used in the data analysis. An IBM-650 computer was used for these computations.

The results of this analysis are shown in Fig. 2 for three sets of data; for two of the cases (II and III) polarized muons were stopped in argon at different magnetic fields and for case I pions were stopped (and hence unpolarized muons were produced). The solid curves were obtained from the analysis of the data and represent the percent amplitude of A compared to the total counting rate. The error bars correspond to an error of one standard deviation in the percent amplitude. The dashed curves are theoretical line shapes centered in each case at the muonium precession frequency predicted from the measured value of the magnetic field. The theoretical lines were computed with the values of τ' and t_0 determined from the data analysis and were normalized to the peak amplitudes of the lines computed from the data.

Resonances are clearly seen in cases II and III at the frequencies which are predicted for muonium precession on the basis of the magnetic field measurements. The observed and predicted resonance frequencies agree within the experimental uncertainty of 0.2 Mc/sec. The observed amplitudes of the resonances are 4 to 5 standard deviations. In case I where unpolarized muons were used, no resonance is observed. In three other cases, not shown here, where polarized muons were used at different magnetic fields, resonances were observed at the precession frequency of muonium; in one additional case with unpolarized muons, no resonance frequency was found. Hence we concluded that muonium is formed in pure argon. Although it is difficult to relate quantitatively the percent amplitude shown in Fig. 2 to the fraction of muons which form muonium, the data do indicate that close to 100% of the muons form muonium in pure argon.

Muonium is of interest principally because it is the simplest system involving a muon and an electron, and hence it offers the greatest promise for a precise study of the interaction between these two particles and thus for a test of the quantum electrodynamic field theory of the muon, electron, and photon system. In particular, it would be of great value to measure the hyperfine structure separation, $\Delta\nu$, in the ground $1\,^2S_{1/2}$ state of muonium. Under the assumption that the muon is a Dirac particle, the theoretical value for $\Delta\nu$ is given by

$$\Delta\nu = \left\{\left(\tfrac{16}{3}\right)\alpha^2 c R_\infty \frac{\mu_\mu}{\mu_0}\right\}\left\{1+\frac{m}{M}\right\}^{-3}\left\{1+\frac{\alpha}{\pi}\right\},$$

in which α = fine structure constant, c = velocity of light, R_∞ = Rydberg constant for infinite mass, m = electron mass, M = muon mass, $\mu_0 = e\hbar/2mc$ = Bohr magneton, $\mu_\mu = e\hbar/2Mc$ = muon magneton. The first bracketed term is the Fermi expression; the second term is a reduced-mass correction; the last term includes the lowest order anomalous magnetic moments of the electron and muon. Use of the known values of the atomic constants[13] gives $\Delta\nu = 4464.0$ Mc/sec. The next order α^2 term has not yet been calculated but is, of course, calculable in principle from a Bethe-Salpeter equation for the bound state of the muon and electron. Comparison of a precise experimental value for $\Delta\nu$ with the theoretical value would provide a critical test of electrodynamics involving the muon and could reveal an anomalous structure of the muon. In view of the abundant formation of muonium that we have found, we are hopeful that a measurement of the hyperfine structure of muonium will be possible and we are preparing to do this experiment.

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