excitation cross sections, only the total conversion coefficients are obtained. The measurements of Edwards and Boehm[3] for Hf^{180} indicate a deviation in the K/L ratio as well as the total conversion coefficient.

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HYPERFINE STRUCTURE OF MUONIUM*

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The discovery of muonium by observation of its characteristic Larmor precession frequency[1] and the rough measurement of its hyperfine structure splitting, $\Delta\nu$, by use of a static magnetic field[2] provided the basic information required to plan a precision measurement of the hfs of muonium in its ground $1\,^2S_{1/2}$ state by a special microwave spectroscopy technique.

If the muon is a particle which obeys the modern Dirac theory and which differs from the electron only in its mass value, then the hfs of muonium can be calculated from the quantum electrodynamic theory of the muon, electron, and photon fields. The result can be expressed as a power series in the small parameters α and (m_e/m_μ), and to terms of order α^2 and $\alpha(m_e/m_\mu)$ is given by[3]

$$\Delta\nu\,(\text{theor}) = \left(\frac{16}{3}\alpha^2 c R_\infty \frac{\mu_\mu}{\mu_0}\right)\left(1+\frac{m_e}{m_\mu}\right)^{-3}\left(1+\frac{3}{2}\alpha^2\right)\left(1+\frac{\alpha}{2\pi}-0.328\frac{\alpha^2}{\pi^2}\right) \times\left(1+\frac{\alpha}{2\pi}+0.75\frac{\alpha^2}{\pi^2}\right)\left(1-1.81\alpha^2\right)\left(1-\frac{3\alpha}{\pi}\frac{m_e}{m_\mu}\ln\frac{m_\mu}{m_e}\right),$$

in which α = fine structure constant, c = velocity of light, R_∞ = Rydberg constant for infinite mass,

μ_μ = muon magneton $(e\hbar/2m_\mu c)$, μ_0 = electron Bohr magneton, m_e = electron mass, and m_μ = muon mass. The first bracketed factor is the Fermi value for the hfs; the second factor is a reduced mass correction; the third factor is the Breit relativistic correction; the fourth and fifth factors are the $g/2$ values for the electron and the muon; the sixth factor is a second order radiative correction; the seventh factor is a relativistic recoil factor. Use of the best modern values of the fundamental atomic constants[4] gives

$$\Delta\nu(\text{theor}) = 4463.13 \pm 0.10 \text{ Mc/sec}.$$

In computing this value we have used

$$(m_\mu/m_e) = (206.76 \pm 0.02),^5 \quad \alpha^{-1} = 137.0391 \pm 0.0006,$$

and[6]

$$\frac{\mu_\mu}{\mu_0} = \left(\frac{\mu_\mu'}{\mu_p}\right)\left(\frac{\mu_p}{\mu_e'}\right) \times \left(1 + \frac{\alpha}{2\pi} - 0.328\frac{\alpha^2}{\pi^2}\right) \Big/ \left(1 + \frac{\alpha}{2\pi} + 0.75\frac{\alpha^2}{\pi^2}\right),$$

in which μ_μ' = muon spin magnetic moment, μ_e' = electron spin magnetic moment, and μ_p = proton magnetic moment. The uncertainty in $\Delta\nu$(theor) is contributed primarily by the uncertainties in the knowledge of α and of (μ_μ'/μ_p).

The effect of a "breakdown of quantum electrodynamics" on the muon magnetic moment has been discussed[7] and any breakdown would also alter the theoretical expression given for $\Delta\nu$. In addition to an alteration in the muon magnetic moment there might also be a structure factor for the muon which could be observed in a measurement of $\Delta\nu$ but not in a measurement of the magnetic moment, as for the case of the proton for which a knowledge of the structure as well as the magnetic moment is needed to determine the value of $\Delta\nu$ for hydrogen.[8]

The present experiment involves the observation of an induced microwave transition between the two hfs magnetic substates of muonium designated by their strong-field quantum numbers $(m_J, m_\mu) = (\frac{1}{2}, \frac{1}{2}) \leftrightarrow (\frac{1}{2}, -\frac{1}{2})$ (m_J and m_μ are the magnetic quantum numbers of the electron and the muon). The transition is observed under approximately strong-field conditions for which the transition frequency is roughly $\Delta\nu/2$. Use of the Breit-Rabi formula[9] allows an exact calculation of $\Delta\nu$ from the observed resonance condition of microwave frequency and static magnetic field. Parity nonconservation in the decay of π mesons[10] results in polarized muons and hence in the initial formation of muonium in only the $m_\mu = +\frac{1}{2}$ states. Parity nonconservation in the decay of the muons[10] allows the determination of the muon spin state through the nonisotropic angular distribution of the decay positrons, and hence the observation of an induced transition between different muon spin states.

The muons are obtained from the Columbia University Nevis synchrocyclotron. The experimental arrangement is shown in Fig. 1 and, apart from the microwave cavity, is similar to that of our previous experiment.[2] The microwave cavity operates in the TM_{110} mode with the axial direction coincident with that of the static magnetic field, and it is fed by a 1-kilowatt klystron amplifier. It is a thin-walled, high-Q cavity filled with highly purified argon gas at a pressure of about 55 atm and is contained in a stainless steel pressure tank. The stopping of a muon in the gas target is indicated by a $12\bar{3}$ coincident count. A decay positron is indicated by a $34\bar{2}$ coincident count and is registered as an "event" if it occurs in the time interval between 0.1 and 3.3 μsec subsequent to the $12\bar{3}$ count. The number of events and the number of $12\bar{3}$ counts are measured, with the microwave field off and with the microwave field on, as a function of the static magnetic field. The ratio R is then computed,

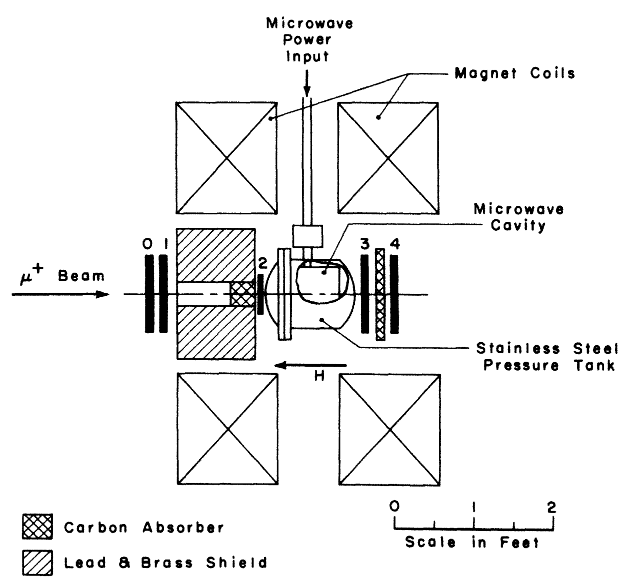

FIG. 1. Experimental arrangement. 0, 1, 2, 3, and 4 are plastic scintillation counters.

where

$$R = \frac{(\text{events}/12\bar{3})_{\text{microwaves on}}}{(\text{events}/12\bar{3})_{\text{microwaves off}}}.$$

If the microwave field induces a transition between the two hfs magnetic substates $(m_J, m_\mu) = (\frac{1}{2}, \frac{1}{2}) \rightarrow (\frac{1}{2}, -\frac{1}{2})$, the angular distribution of the decay positrons will be changed from $C(1 + A \cos\theta)d\Omega$ to $C(1 - A \cos\theta)d\Omega$, in which C is a constant, $A \simeq \frac{1}{3}$, and θ is the angle between the direction of the static magnetic field and the direction of emission of the positron. Hence the transition should be observed as an increase of R to a value greater than 1.

An observed curve is shown in Fig. 2. Measured values of the quantity R are plotted vs values of the magnetic field for a fixed microwave frequency; the solid curve has a Lorentzian form whose constants are chosen by use of the Yale IBM-709 computer to give a least-squares fit to the experimental data. The linewidth of 120 gauss is due primarily to the high microwave power level used. Another resonance curve was obtained with about $\frac{1}{4}$ the power level and it has a linewidth of 44 gauss. A resonance curve was also obtained at a reduced argon pressure of 35 atm in order to test for a dependence of $\Delta\nu$ on pressure. Within our experimental accuracy no pressure shift was observed, which is consistent with the known pressure shift for hydrogen in argon.[11] It was observed that the resonance curve disappeared when 200 parts per million of air was added to the pure argon. We believe that this probably indicates the occurrence of chemical reactions of oxygen or nitrogen molecules with muonium, which is similar chemically to atomic hydrogen.

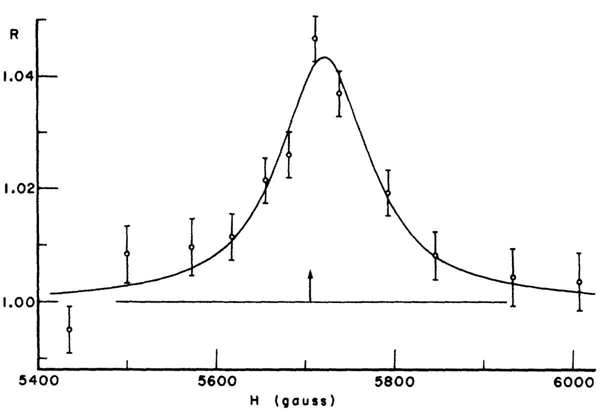

FIG. 2. Experimental values of R vs static magnetic field for a microwave frequency of 1850.08 Mc/sec, and with an argon pressure of 55 atm. The solid curve is a least-squares fit Lorentzian curve with $H_{\text{center}} = 5725$ gauss and with width = 120 gauss. Error flags are ±(one sample standard deviation). The arrow indicates the theoretical line center, ignoring the pressure shift.

On the basis of four resonance curves we determine the hfs splitting of muonium in its ground $1\,^2S_{1/2}$ state to be

$$\Delta\nu(\text{expt}) = 4461.3 \pm 2.2 \text{ Mc/sec}.$$

The error quoted is due primarily to the inhomogeneity of the magnetic field, but it also includes an estimated upper limit of the unknown pressure shift. The experimental value agrees with the theoretical value. Experiments are being planned with a more homogeneous magnetic field in order to obtain higher accuracy.

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