this peak to the autoionization of the states $\mathrm{Ar}[\cdots 3s^3 3p^4 4sns, np\ (n \geq 5)]$, as indicated in Fig. 2. At energies from 16.6 eV up to 50 eV all curves stay close to zero indicating that no higher superexcited states are important in the ion energy range investigated. All peaks are strongly energy dependent and those two which correspond to the states $\cdots 3s3p^6 4s$ and $\cdots 3s3p^6 4p$ show an energy dependence typical for processes which involve a curve crossing.[7,8]

To the portion of the spectrum below 9 eV both process (1a) as well as process (1b) if it occurs at small separations can contribute. However, a contribution of autoionizations at large separations can be excluded. Therefore the spectrum should be continuous in this region, and it is interesting that in spite of this some reproducible structure is resolved in our curves, especially at low ion energies.

In a forthcoming publication we will give further experimental data and a more detailed discussion of the structure and the energy dependence of the electron energy distributions.

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DETERMINATION OF THE MUONIUM HYPERFINE SPLITTING AT LOW PRESSURE FROM A FIELD-INDEPENDENT ZEEMAN TRANSITION*

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The ground-state hyperfine interval $\Delta\nu$ of muonium has been redetermined in argon by measuring the $(1,1)\leftrightarrow(1,0)$ Zeeman frequency ν_1 at that external-field value where $\partial\nu_1/\partial B = 0$. The measurements were performed with good statistics at much lower argon pressures than heretofore, greatly reducing uncertainties in extrapolating $\Delta\nu(p)$ to zero pressure. Our result, $\Delta\nu(0) = 4463.317 \pm 0.21$ MHz, disagrees with the value found by Thompson et al. in Ar, but is consistent with their result in Kr.

The hyperfine structure of muonium is, because of the pointlike nature of its nucleus, potentially one of the best sources for a precise value of the fine-structure constant α. Hughes and his co-workers at Yale have in fact reported an increasingly accurate series[1,2] of values for the ground-state hyperfine interval $\Delta\nu$. There remain, however, two essential difficulties of interpretation: (1) the extrapolation to zero buffer-gas density of the actually observed frequencies; (2) uncertainties in the value of the muon magnetic moment μ_μ.[3] The "hyperfine pressure shift" (1) is a well-known phenomenon in the case of H and its heavier isotopes[4] where it has been shown to exhibit a linear dependence on pressure. This knowledge, acquired at pressures below 270 Torr, may however not be applied directly to the case of muonium, where most of the data have so far been obtained at pressures above 2.5×10^4 Torr. The linear extrapolation used by the Yale group is hence subject to question[5]; their recent observation[2] that the frequencies $\Delta\nu$ in two buffer gases (Ar, Kr) extrapolate to different zero-pressure values (see Fig. 3) is indicative of nonlinear dependence.

We report here a precise determination of $\Delta\nu$

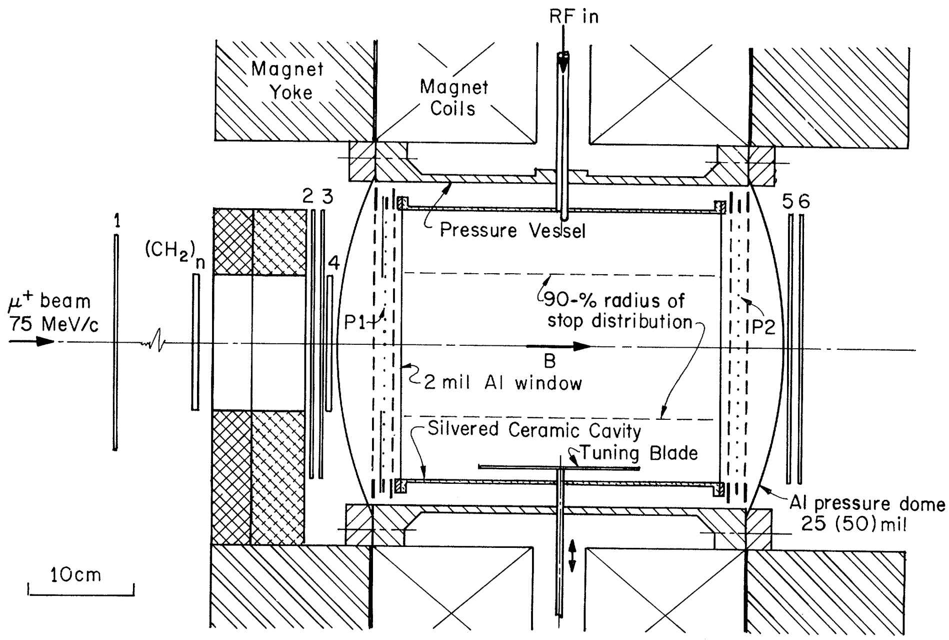

FIG. 1. Experimental setup used for observing the (F, M_F) $(1,1) \leftrightarrow (1,0)$ Zeeman transition of muonium in a fixed field ($B = 11.353$ kG). 1 through 6 are scintillators (light pipes not shown), P_1 and P_2 proportional counters. Signatures: stop $= (234\overline{5})$, with discriminator on 4 set to accept only stopping particles; superstop $=$ (stop P_1 P_2); $e_F = (\overline{13}56)$; $e_B = (\overline{1}23\overline{5}\ \overline{\text{stop}})$.

performed at considerably lower pressures than heretofore in order to alleviate the difficulty just discussed. Both the nonlinearity and the absolute magnitude of the shift become unimportant as sources of systematic error as the pressure is decreased. Thus at 3.15×10^3 Torr (our lowest point) the total pressure-shift correction is of the order of 20 ppm, i.e., comparable with the difference between the extrapolated Ar and Kr values of Ref. 2.

The quantity directly measured in the present work is the frequency ν_1 of the $(1,1) \leftrightarrow (1,0)$ Zeeman transition; the microwave resonance is detected through the attendant change in muon polarization. Thus this measurement is a variant of the Yale "high-field" experiment,[1,6] and we may confine ourselves to the discussion of significant departures from that work. These departures, primarily aimed at maximizing the ratio of useful decays (from muons stopping within the gas-filled microwave cavity) to background decays (from muon stops in the walls), are the following:

(a) External magnetic field B.—The frequency ν_1, as a function of B, goes through a maximum at $B_0 = (\Delta\nu/2\mu_0^e)[(g_j + g_\mu')/(g_j - g_\mu')](-g_j g_\mu')^{-1/2} = 11.353$ kG. Thus near B_0, ν_1 becomes to first order field independent, and inhomogeneities have only a second-order effect: An rms $\delta B/B_0$ of 1% induces only a shift $\delta\nu_1/\nu_1$ of -7 ppm. By working at B_0 we can readily use a large-volume cavity; it is however necessary to sweep the resonance in frequency.

(b) Proportional counters.—Two such detectors (P_1 and P_2 in Fig. 1) were provided within the pressure vessel to exclude muon stops in the Al end windows. P_1, active only over a 12.5-cm circle, acted as an additional collimator. The energy resolution was such that $\overline{P}_2$, firing on positrons, suppressed only a very small fraction of decays.

(c) Microwave cavity.—In order to separate the muon beam radially from the cavity walls (see Fig. 1), we chose TM_{210} ($r = 12.7$ cm) instead of TM_{110} ($r = 9.5$ cm). A further advantage of this mode is its greater rf field homogeneity over the volume of interest. By making the body of the cavity out of an appropriate material (Corning Ceramic 9692, expansion coefficient $< 2 \times 10^{-8}/$°C), excellent thermal stability is achieved without feedback systems.

(d) Stops distribution.—This function $f(\vec{r})$, as well as its product with the relevant solid angle $\Omega(\vec{r})$ for positron detection, were determined directly in a separate experiment. This information is important for predicting the resonance line shape. The product $f\Omega$ had a 90% radius of 6.5 cm.

Backward-decay muons [~75 MeV/c, ~1-g/cm^2-wide range curve in $(CH_2)_n$, ~55% polarization] from a muon channel[7] were used, producing ~300 "superstops" per second in argon gas at 5 atm. The corresponding mean e^+ rate (in a 5-μsec gate) was ~40/sec in either of the two telescopes of Fig. 1; thanks to the excellent beam duty cycle (>50%), the accidentals rate was so low (<8% backward) that both telescopes contributed almost equally good data.

The data were collected through a gate of 500 μsec, synchronized with the stochastic system of the cyclotron, the rf power being present during alternate gate periods. The four kinds of data (rf on/off, backward/forward) were, after digitron[8] analysis, stored in four 100-channel banks of a pulse-height analyzer and later transferred to magnetic tape.

Resonances were obtained at 3.15×10^3 and 12.05×10^3 Torr (two runs) of argon.[9] The raw data were reduced (in order to virtually eliminate possible time-dependent effects) by dividing each of the four sets obtained at a given frequency into 17 bins of 250 nsec each, computing [(rf on)−(rf off)]/(rf off) for each of these, and summing. The data points in Fig. 2(a), shown as an illustrative example, were so obtained. A single Lorentzian was fitted to each resonance curve to obtain the center frequency. The predicted line shape, based on a direct power determination and the measured function $\Omega(\vec{r})f(\vec{r})$, was indeed virtually indistinguishable from a Lorentzian of the observed width. Several alternative methods of data reduction always gave center frequencies in statistical agreement with those from the method just described.

Because the muons were stopped here in a limited volume of sensibly uniform rf power distribution, we could observe the time-dependent evolution of the muon polarization $\vec{P}_\mu(t)$, i.e., exhibit the Majorana-Rabi[10] transition probability. Figure 2 shows an example of such a "precession curve." By fitting a family of such curves for the rf powers and the center of the resonance, results statistically consistent with the analysis described above were obtained.

Our experimental results (corrected to 0°C) are

$$\nu_1(3.15\times 10^3 \text{ Torr}) = 1922.719 \pm 0.005 \text{ MHz}, \quad (1a)$$

$$\nu_2(1.21\times 10^4 \text{ Torr}) = 1922.626 \pm 0.003_4 \text{ MHz} \quad \text{(mean of two runs)}. \quad (1b)$$

By use of a linear extrapolation these yield

$$\nu_1(0 \text{ Torr}) = 1922.752 \pm 0.009 \text{ MHz}, \quad (2)$$

where the uncertainty is a combination of statistical error (7 kHz) and systematic uncertainties (1 kHz), and a fractional pressure shift (FPS)

$$(1/\nu_1)(\partial\nu_1/\partial p) = (5.44 \pm 0.45)\ 10^{-9}/\text{Torr}. \quad (3)$$

Frequency (2) in turn corresponds to

$$\Delta\nu(0) = 4463.317 \pm 0.021 \text{ MHz} \quad (\pm 5 \text{ ppm}) \quad (4)$$

adopting the current values[11] of the constants. To compare with the measured value of f_μ/f_p, we

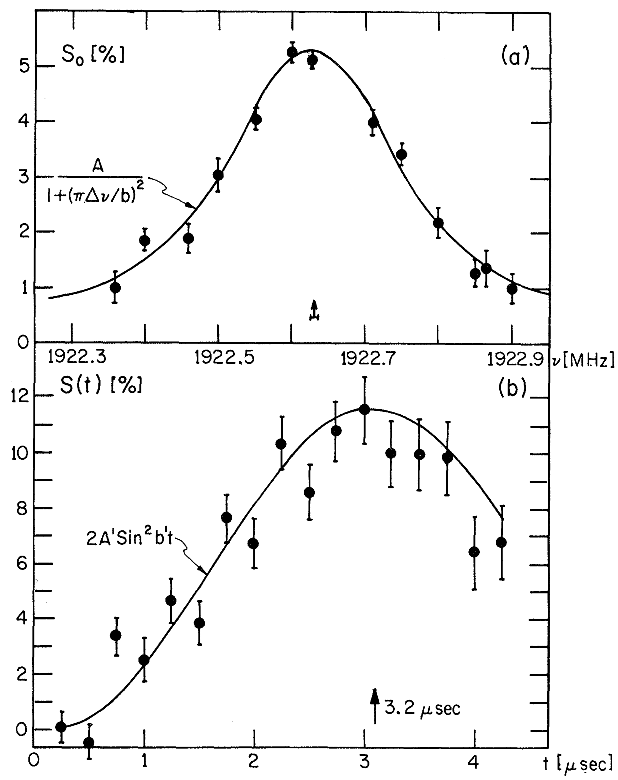

FIG. 2. (a) Resonance curve for the field-independent $(F, M_F) = (1,1) \longleftrightarrow (1,0)$ transition in argon at 12.05×10^{-3} Torr. Error bars (1 standard deviation) represent counting statistics. The solid curve S_0 is a Lorentzian line shape giving the best fit. (b) Time-dependent signal $S(t)$ corresponding to the central point (1922.632 MHz) on the curve in (a). Error bars again represent statistical standard deviations, and the solid curve is the Majorana-Rabi transition rate giving the best fit. Note that the parameters A' and b' differ slightly from A and b because $S(t)$ is observed over a finite time interval.

take the ratio with the hydrogen hf splitting[12]:

$$\frac{\Delta\nu(\mu e)}{\Delta\nu(pe)}=\left(\frac{\mu_\mu}{\mu_p}\right)\left(\frac{1+m_e/m_p}{1+m_e/m_\mu}\right)^3(1+\delta_p-\delta_\mu). \qquad (5)$$

Here δ_μ (179 ppm) and δ_p (35 ppm) represent the relativistic-recoil and finite-size corrections; the various electrodynamic corrections, identical for the two atoms, cancel in the ratio to first order. Note that no allowance is made in (5) for proton polarizability.[12] With (4) and $\Delta\nu(pe) = 1420.405\,75$ MHz,[13] (5) yields

$$\mu_\mu/\mu_p = 3.183\,351 \pm 0.000\,016. \qquad (6)$$

The ratio f_μ/f_p measured in water[13] is 3.183 38 ± 0.0004, and differs from (6) only by less than one standard deviation. The difference goes, however, in the sense of Ruderman's[3] shielding corrections, and if taken seriously amounts to 10 ppm. Part of this difference might be attributed to the polarization correction omitted in (5).

For a discussion of the pressure shift we turn to Fig. 3, where both our $\Delta\nu(p)$ and those of the Yale group are plotted.[14] Our FPS (3) is closer to the value reported[4] for atomic H in Ar $[-(4.78 \pm 0.03)\times 10^{-9}]$ than to the value $-(4.07 \pm 0.25)\times 10^{-9}$ given in Ref. 2 for muonium in Ar. Note however that extrapolating with either FPS from our point at 3.15×10^3 Torr yields only a difference of 4 ppm in $\Delta\nu(0)$, and furthermore that the lowest

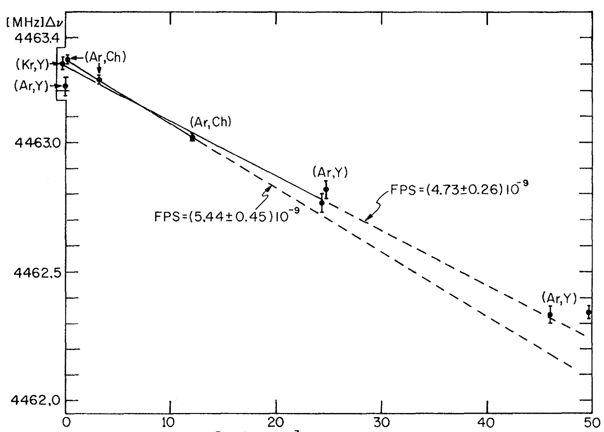

FIG. 3. Observed values of $\Delta\nu$ versus argon density. Points marked (Ar, Ch) are the present results, while the Yale results in argon and krypton are indicated as (Ar, Y) and (Kr, Y), respectively. The points at zero density are extrapolated intercepts and not measured values.

Yale point (at 2.5×10^4 Torr) is quite compatible with our FPS. By including this latter point with our data in a straight-line fit, we find

$$(1/\Delta\nu)(\partial\Delta\nu/\partial p) = -(4.73 \pm 0.26)\times 10^{-9}/\text{Torr}, \quad (7)$$

in even better agreement than (3) with the FPS found for H in Ar, while $\Delta\nu(0)$ is changed only 3.8 ppm from (4). Our disagreement with Ref. 2 thus stems mainly from their high-pressure points, as is clear from Fig. 3. As our $\Delta\nu(0)$ is consistent with the value observed[2] in Kr (where the Yale group worked with lower number densities than in Ar!), we may conclude that the disagreement in the Ar measurements is due to nonlinearity above 3×10^4 Torr.

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