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NEW VALUE FOR THE FINE-STRUCTURE CONSTANT α FROM MUONIUM HYPERFINE STRUCTURE INTERVAL*

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We have remeasured the ground-state hyperfine structure interval, $\Delta\nu_M$, of muonium (μ^+e^-) to a much higher precision than previously.[1,2] The result is important for obtaining an independent measurement of the fine-structure constant α, and hence also for an understanding of proton structure.[3]

The experiment was very similar to that described previously.[1] The Nevis synchrocyclotron of Columbia University provided a longitudinally polarized beam of positive muons, which were stopped in high-pressure argon gas, and formed polarized muonium. A microwave-induced transition between the high-field states $(m_J, m_\mu) = (\frac{1}{2}, \frac{1}{2})$ and $(\frac{1}{2}, -\frac{1}{2})$ (m_J and m_μ are the magnetic quantum numbers of the electron and the muon) changed the angular distribution of the decay positrons from the muons, notably near 0° (forward) and 180° (backward) where we observed the positrons. For fixed microwave frequency, the ratio of decay positrons to stopped muons, as a function of magnetic field, has a resonant behavior as shown in Fig. 1. A great increase in precision as compared to the original resonance experiment[1] was achieved by (1) obtaining much narrower resonance lines through use of a more homogeneous static magnetic field and low microwave power, (2) improving the counting statistics very substantially in a long experiment in which positrons were observed in both the forward and backward directions, (3) improving the reliability and stability of all components in the experiment.

The argon gas perturbs the muonium atoms and produces a fractional change in the measured value of $\Delta\nu_M$ which is proportional to the argon density to first order. This density shift (or pressure shift) has been measured[4] accurately for the isotopes of hydrogen in argon at pressures up to 40 mm Hg. From the results of a run carried out by us in December 1962, with argon pressures of 68 atm and 35 atm, it was clear that the pressure shift was present; another run which extended the measurements to argon pressures as low as 10 atm was carried out in January and February 1964. The results of both runs are shown in Fig. 2. The errors in the individual points come about equally from statistical counting uncertainties and from uncertainties in the magnetic field measurements.

These points have been fitted to both a straight line and a parabola. The quadratic term was found to be very small, and consistent with zero, so all results are based on the linear fit. We found a fractional pressure shift of $(-4.05 \pm 0.49) \times 10^{-9}$ (mm Hg)$^{-1}$ at 0°C for muonium in argon, which is in good agreement with the corresponding values of $(-4.77 \pm 0.12) \times 10^{-9}$ for hydrogen, $(-4.52 \pm 0.40) \times 10^{-9}$ for deuterium, and $(-5.05 \pm 0.15) \times 10^{-9}$ for tritium in argon determined by optical pumping.[4] We obtain

$$\Delta\nu_M(\mathrm{expt}) = 4463.15 \pm 0.06 \text{ Mc/sec } (\pm 13 \text{ ppm}) \quad (1)$$

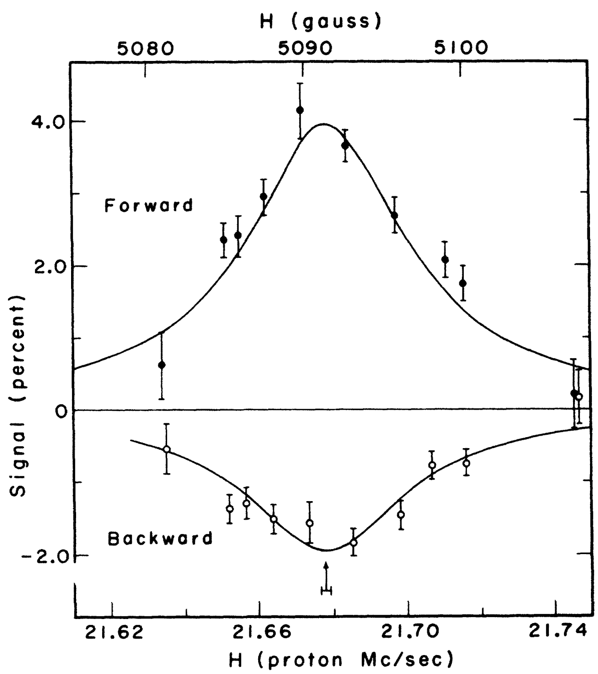

FIG. 1. Observed signal (R-1, where R is defined in reference 1) at a microwave frequency of 1823.061 Mc/sec, in 50-atm argon, as a function of magnetic field. The curves are best-fit computed line shapes. The arrow indicates the common center of the fitted curves, and the flag on it is ±(one standard deviation). The width of the curves was taken from the measured cavity Q and the microwave power.

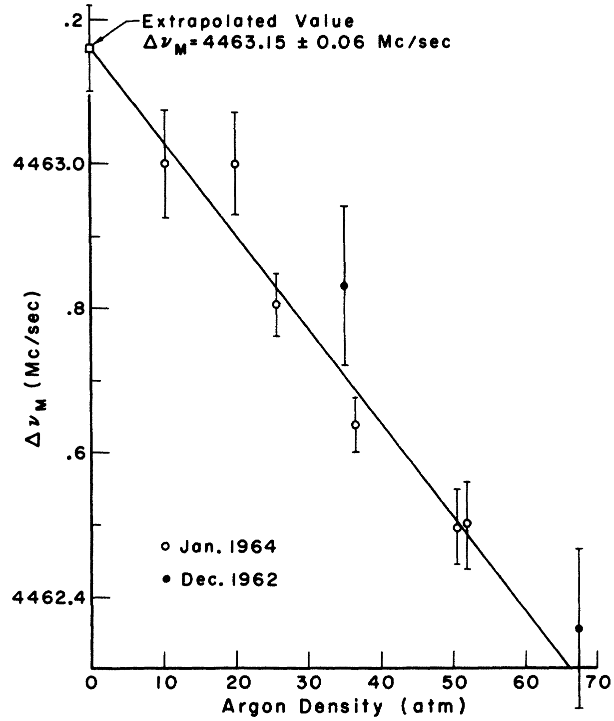

FIG. 2. $\Delta\nu_M$ as a function of argon gas density (which is given in units of equivalent pressure at 0°C assuming a perfect gas law; these numbers are very close to the actual pressures measured during the experiments at temperatures of about 34°C).

as the value of $\Delta\nu_M$ extrapolated to zero pressure, where the quoted error is ±(one standard deviation).

The theoretical value of $\Delta\nu_M$ may be written in the form[5]

$$\Delta\nu_M(\text{theor}) = (16\alpha^2 cR_\infty/3)(\mu_\mu/\mu_p)(\mu_p/\mu_e)(1+m_e/m_\mu)^{-3}(1+a_e)^2(1+\epsilon_1+\epsilon_2)(1-\delta_\mu), \tag{2}$$

where

$$a_e = \alpha/2\pi - 0.328\alpha^2/\pi^2, \qquad \epsilon_1 = -(1-\ln 2)\alpha^2, \qquad \epsilon_2 = -(8\alpha^3/3\pi)\ln\alpha(\ln\alpha - \ln 4 + 281/480),$$

$$\delta_\mu = +(3\alpha/\pi)(m_e/m_\mu)\ln(m_\mu/m_e).$$

If we substitute the currently accepted values[6-8] (with errors in parentheses given in "parts per million")

$$R_\infty = 109\,737.31\ \text{cm}^{-1}\ (\pm0.1\ \text{ppm}), \quad \mu_e/\mu_p = 658.2106\ (\pm1\ \text{ppm}), \quad c = 2.997\,925\times10^{10}\ \text{cm/sec}\ (\pm1.3\ \text{ppm}),$$

$$m_\mu/m_e = 206.765\ (\pm13\ \text{ppm}), \quad \alpha^{-1} = 137.0388\ (\pm9\ \text{ppm}), \quad \mu_\mu/\mu_p = 3.18338\ (\pm13\ \text{ppm}) \tag{3}$$

(μ is the magnetic moment of the free particle), we obtain

$$\Delta\nu_M(\text{theor}) = 2.632\,936\times10^7\alpha^2(\mu_\mu/\mu_p)\ \text{Mc/sec}\ (\pm1.5\ \text{ppm}),$$

$$= 4463.15 \pm 0.10\ \text{Mc/sec}\ (\pm22\ \text{ppm}). \tag{4}$$

The excellent agreement of the experimental and theoretical values of $\Delta\nu_M$ as given by Eqs. (1) and (4), respectively, may be regarded as a further confirmation[9] that the muon, like the electron, is a Dirac particle and that it has the conventional electrodynamic coupling. Alternatively, the theoretical basis for Eq. (2) may be assumed to be correct and the experimental value for $\Delta\nu_M$ may be used to determine a value for the fine-structure constant α. This procedure is reasonable since α^2 is the least accurately known constant in Eq. (2). We obtain

$$\alpha^{-1} = 137.0388 \; (\pm 9 \text{ ppm}). \tag{5}$$

This value is in excellent agreement with the value of α given above which is obtained from a measurement of the fine structure of deuterium.[7] A more accurate value for α is obtained by combining the two results to give

$$\alpha^{-1} = 137.0388 \; (\pm 6 \text{ ppm}). \tag{6}$$

A precise value for α is of interest because it is a basic atomic constant. In addition, however, a precise value for α is required for the comparison of the experimental and theoretical values of the hyperfine structure of hydrogen in its gound state.[3] The experimental value for $\Delta\nu_H$ is[10]

$$\Delta\nu_H(\text{expt}) = 1\,420\,405\,751.800 \pm 0.028 \text{ cps}. \tag{7}$$

The theoretical formula for $\Delta\nu_H$ is

$$\Delta\nu_H = (16\alpha^2 c R_\infty/3)(\mu_p/\mu_e)(1+m_e/m_p)^{-3}(1+a_e)^2 \times (1+\epsilon_1+\epsilon_2)(1-\delta_p), \tag{8}$$

where

$$\delta_p = (35 \pm 3) \times 10^{-6};$$

in which δ_p is a term which accounts for proton recoil and proton structure.[11] If we use the values of the relevant constants as given in Eq. (3) (together with the value $m_p/m_e = 1836.12 \pm 0.02$) and the value of α from Eq. (6), we obtain

$$\Delta\nu_H(\text{theor}) = (1420.342 \pm 0.024) \text{ Mc/sec}. \tag{9}$$

Hence

$$\frac{\Delta\nu_H(\text{expt}) - \Delta\nu_H(\text{theor})}{\Delta\nu_H(\text{expt})} = 45 \pm 17 \text{ ppm}. \tag{10}$$

The discrepancy between the theoretical and experimental values for $\Delta\nu_H$ is relatively large. Note that the uncertainty in α is the principal contribution to the error ±17 ppm in Eq. (10). Our determination of α from the muonium hfs has provided a completely independent determination of α in excellent agreement with the value of α from deuterium fine structure. Hence the existence of a real discrepancy between the theoretical and experimental values of $\Delta\nu_H$ seems certain and cannot easily be ascribed to an incorrect value of α. Since the theoretical foundation for the calculation of δ_p as well as some of the approximations involved in its evaluation are uncertain, it appears that this discrepancy is probably due to an incorrect theoretical value for δ_p.

We may also compare our result for $\Delta\nu_M$ with $\Delta\nu_H$ by considering the ratio $\Delta\nu_M/\Delta\nu_H$. Its theoretical value is:

$$(\Delta\nu_M/\Delta\nu_H)(\text{theor}) = (\mu_\mu/\mu_p)(1+m_e/m_p)^3(1+m_e/m_\mu)^{-3} \times (1-\delta_\mu)/(1-\delta_p)$$
$$= (3.142\,76 \pm 13 \text{ ppm})(1-\delta_\mu)/(1-\delta_p). \tag{11}$$

The experimental value is:

$$(\Delta\nu_M/\Delta\nu_H)(\text{expt}) = 3.142\,17 \pm 0.000\,04 \; (\pm 13 \text{ ppm}). \tag{12}$$

We can combine Eqs. (11) and (12) and regard δ_p as the unknown and thus obtain

$$\delta_p = (-9 \pm 18) \times 10^{-6},$$

which differs markedly from the theoretical value $\delta_p = 35 \times 10^{-6}$. The result of this comparison is essentially the same as that exhibited in Eq. (10). However, this particular method of comparison has the advantage that in the ratio $(\Delta\nu_M/\Delta\nu_H)$(theor) various rather complicated electrodynamic radiative corrections cancel and hence an error in the calculated value of one of these terms and also the omission of many still higher order terms are not important.

A detailed report on the muonium experiments will soon be submitted to The Physical Review.

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$$F = \tfrac{1}{16}\alpha^2 C R_D\left[1 + \tfrac{5}{8}\alpha^2 + \left(1 - \frac{m}{M_D}\right)\frac{\alpha}{\pi} - 0.656\frac{\alpha^2}{\pi^2} - \frac{2}{\pi}\alpha^3 \ln\alpha^{-1}\right].$$

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STRUCTURE IN THE PION-PROTON TOTAL CROSS SECTION BETWEEN 2.5 AND 5.5 BeV/c†

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The total cross sections of $\pi^\pm$ on protons in the momentum interval 2.5 to 5.5 BeV/c have been measured with high precision in a transmission experiment at the Brookhaven alternating gradient synchrotron. This Letter reports the new preliminary data obtained with a statistical accuracy of 0.05% for π^--p and 0.08% for π^+-p cross sections and at momentum intervals of 100 MeV/c. The results indicate two statistically significant new pion-nucleon resonances, one in each of the two isotopic spin states. Previous measurements[1,2] in this momentum interval with a statistical accuracy of 0.5%-1% did not reveal any structure. The newly found resonances and their characteristics are summarized in Table I.

The secondary pion beam was taken from a Be target at a production angle of +9° to the internal proton beam of the AGS. The particles were focused and momentum analyzed onto an intermediate-focus momentum slit, set for a full width of 1.0% at half-height. The second half of the beam transport system was a reflection about the first focus of the first half with both analyzing magnets deflecting the beam by angles of 9°. The relative momenta were set to better than 0.05% using a Hall plate and a nuclear fluxmeter. The absolute momenta are estimated to be known to better than 0.25%.

The pions were identified by a differential gas Cherenkov counter[3] situated directly behind the first focus. The angular acceptance of the Cherenkov radiation was set at 10 milliradians. This was done in order to count efficiently π mesons in a beam which had a vertical angular divergence of ±3 milliradians and a horizontal angular divergence of ±5 milliradians at the first focus. Multiple air scattering was reduced by vacuum pipes and helium bags. The final pion image had a full width at half height of one inch or less. The π-meson flux varied from 2×10^4/pulse to 4×10^4/pulse depending upon the primary-beam energy and secondary-beam momentum.

The hydrogen target[4] was 120 inches long with its center situated 170 inches ahead of the second focus. It was of special, double jacketed design to provide long-term density stability.