First Observation of the Ground-State Hyperfine-Structure Resonance of the Muonic Helium Atom

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The first measurement of the hfs interval $\Delta\nu$ for the muonic helium atom $(^4\mathrm{He}^{++}\mu^-e^-)^0$ is reported. In terms of its electronic structure, it is a heavy isotope of hydrogen. Polarized atoms are formed by stopping polarized negative muons in a helium-gas target at 19.4 atm with a 1.5% admixture of Xe. The ground-state hfs splitting $\Delta\nu$ was measured through observation of a microwave magnetic-resonance transition at zero magnetic field. After correction for the hfs pressure shift, we determine $\Delta\nu = 4464.95(6)$ MHz (13 ppm).

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Muonic helium, $(^4\mathrm{He}^{++}\mu^-e^-)^0$, is an atom consisting of a $^4\mathrm{He}^{++}$ nucleus, a negative muon, and an electron. In the ground state the muon orbits the $^4\mathrm{He}^{++}$ nucleus in a $Z=2$ hydrogenic 1S state with energy and radius scaled by the muon reduced mass. Therefore, the $(^4\mathrm{He}^{++}\mu^-)^+$ system is a factor $(1/Z)\,(m_e/m_\mu) \approx 1/400$ smaller than a hydrogen atom and can be regarded as a "pseudonucleus" with a size intermediate between atomic and nuclear dimensions ($r \sim 130$ fm). To this ion, $(^4\mathrm{He}^{++}\mu^-)^+$, of effective charge $Z_{\mathrm{eff}}=1$ the electron is bound in a normal atomic 1S orbit. The atom can thus be considered as one hydrogenic system inside another. Chemically it behaves like a heavy isotope ($M=4.11$ amu) of hydrogen. The $(^4\mathrm{He}^{++}\mu^-e^-)^0$ is the simplest system for observing the electromagnetic interactions of the bound electron, including QED effects, in a muonic atom. In quantum mechanics, it may be described as an electromagnetic three-body bound state without exchange interaction.

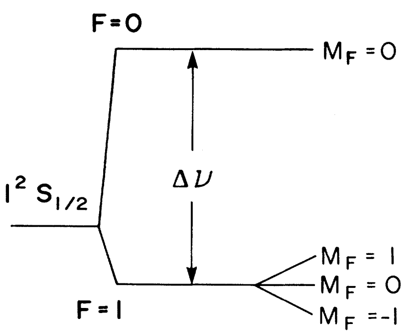

FIG. 1. Diagram of the hyperfine structure and low-field Zeeman splitting in the ground state of the muonic helium atom.

We have performed an experiment at the Schweizerisches Institut für Nuklearforschung (SIN) to measure the hyperfine interaction[1,2] between muon- and electron-spin magnetic moments in this simple muonic atom. The hyperfine-structure interval (see Fig. 1) is expressed nonrelativistically by the expectation value of the Fermi contact interaction between electron and muon,

$$\Delta\nu_{\mathrm{F}} = \frac{32\pi}{3h}\frac{m_e}{m_\mu}\mu_{\mathrm{B}}^2\int \psi^*(\vec{r}_\mu,\vec{r}_e)\delta^3(\vec{r}_\mu-\vec{r}_e) \times \psi(\vec{r}_\mu,\vec{r}_e)\,d^3r_\mu\,d^3r_e\,, \qquad (1)$$

where μ_{B} is the Bohr magneton and $\psi(\vec{r}_\mu,\vec{r}_e)$ is the wave function of the atom in the ground state. The "pseudonucleus" picture leads one to divide this integral into two parts: a leading term $\Delta\nu_{\mathrm{F}}^0$, given by the Fermi formula for a point nucleus of mass $M = m_\mu + m_{^4\mathrm{He}^{++}}$,

$$\Delta\nu_{\mathrm{F}}^0 = \tfrac{16}{3}\alpha^2 R_\infty c(m_e/m_\mu)(1+m_e/M)^{-3} = 4516.96\ \mathrm{MHz} \qquad (2)$$

and a correction term, which contains static as well as dynamic contributions associated with the finite size of the pseudonucleus. Additional correction terms arise from relativistic, radiative, and recoil effects. The full theoretical expression for the hfs splitting $\Delta\nu$ can thus be written as

$$\Delta\nu = \Delta\nu_F(1+\delta_{rel}+\delta_{rad}+\delta_{rec}). \tag{3}$$

A precision determination of $\Delta\nu$ provides a very sensitive measurement of both the μ^-, e^- interaction in this atom and of the wave function $\psi(\vec{r}_\mu, \vec{r}_e)$ in the region of the pseudonucleus. In particular, this is the first case where the Fermi contact interaction is precisely tested for two particles of like charges.

Negative muons are stopped in helium gas with a 1.5% admixture of xenon. First the $(^4He^{++}\mu^-)^+$ ion is formed by muon capture by a He atom, and subsequently the $(^4He^{++}\mu^- e^-)^0$ atom is formed by electron capture from a Xe atom. Precession measurements revealed that small Xe admixtures of about 0.5% result in incomplete neutralization of the $(^4He^{++}\mu^-)^+$ ions. It has been shown in a previous experiment[3,4] that in the $(^4He^{++}\mu^- e^-)^0$ atom about (2–3)% of the initial muon polarization is retained in these processes. This residual polarization is a necessary prerequisite for a microwave magnetic-resonance experiment similar to the one in muonium.[5] Microwave magnetic resonance transitions ($\Delta F = \pm 1$, $\Delta M_F = \pm 1$) alter the muon polarization and can be detected via the decay-electron angular asymmetry.

The apparatus for the microwave resonance experiment is shown in Fig. 2. Polarized negative muons from the SIN $\mu E4$ channel at 55 MeV/c momentum are stopped in a gas target containing a mixture of helium and 1.5% xenon at 20 atm. The gas is continuously purified by circulation over hot titanium. The beam enters through a domed pressure window made of thin beryllium copper sheet (250 μm). Flat copper foils (25 μm) and the inner walls of the brass pressure vessel define a cylindrical microwave cavity. The microwave power is iris coupled into this cavity, which resonates in the TM_{320} mode and is tunable between 4460 and 4500 MHz. Magnetic shielding with high-permeability metal sheets keeps the residual magnetic field below 20 mG within the target volume.

Muons stopping in the target (μ_S) are identified by plastic scintillation counters. Since only high-Z materials surround the target gas, most muons stopped in the walls are captured by nuclei. Muon decay electrons (e_F, e_B) therefore originate predominantly from stops in the gas. They are counted by two plastic scintillator telescopes (F, B) located forward and backward with respect

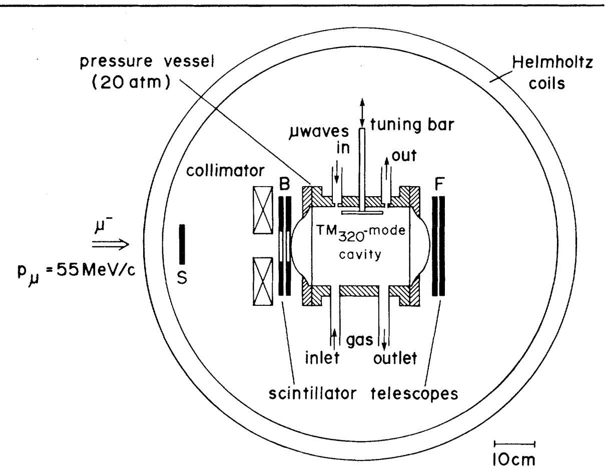

FIG. 2. Schematic view of the apparatus. The Helmholtz coils are used for muon-spin rotation. A cylindrical high-permeability metal shield (diameter 50 cm, length 100 cm) was installed (not shown in the figure) during the microwave magnetic-resonance experiment to reduce the stray magnetic fields.

to the beam direction. The backward telescope has a 8×8 cm^2 hole in the center to admit the collimated muon beam. Under typical running conditions $5\times 10^4 \mu_S$/s are recorded, of which 2×10^4 s^{-1} are stopped in the target gas. Decay-electron rates in each telescope are typically 1.2×10^3 s^{-1}, which is about the rate expected for a detector covering 7% of the solid angle with respect to the target.

Data are taken modulating the microwave power between on and off at 0.5 Hz with the microwave frequency fixed at a value near the expected resonance frequency. At the end of a run (typically 40 min or 10^8 stopped muons) a normalized signal, $\mathcal{S}$, is calculated for each of the telescopes separately with $\mathcal{S} = (e/\mu_S)_{on}/(e/\mu_S)_{off} - 1$. By delayed coincidence the acceptance of electrons has been electronically confined within a window of 0.5–6 μs after a stopped muon. Thus background contributing to e_F or e_B from muons in the high-Z walls is reduced to less than 1% of the counting rate.

By reversing the μ-channel polarity we can stop positive muons in the same target. Then muonium is formed[6] and its hyperfine resonance can be observed[7] with the cavity tuned to the muonium hfs frequency of 4463.5 MHz. From the width of the resonance signal, the average microwave power over the μ^- stopping distribution within the cavity is obtained. The signal height, which is proportional to the analyzing power of the apparatus for microwave transitions, allowed us to estimate the expected $(^4He^{++}\mu^-e^-)^0$ signal height. In addition, the observed muonium resonance frequency provides an experimental value for the pressure-shift correction in $(^4He^{++}\mu^-e^-)^0$.

Because of the small muonic polarization in muonic helium, which is twenty times smaller than that in muonium, we expected a hfs microwave signal in $(^4He^{++}\mu^-e^-)^0$ of about 0.1%. As a consequence it took about 12 h to obtain a statistically significant datum point. Taking into account this weak signal and the narrow signal width of about 0.5 MHz, it is obvious that a search over only a small range of frequencies could be carried out in a reasonable amount of time.

In view of this it should be noted that the theoretically predicted values[1,2,8-13] for $\Delta\nu$ ranged from early values of 4511 MHz (hydrogenic wave functions with static finite-size correction[8]) through 4494.1 MHz and 4478.7 MHz (variational calculation using 35-term[9,10] and 455-term wave functions[11]) to 4462.6 MHz (static and dynamic finite-size correction using a second-order perturbation calculation[12]). After some unsuccessful searches at the higher frequencies predicted initially, we finally found a signal at 4465.2 MHz. The signal did manifest itself in both an increase of the backward telescope counting rate and a decrease in the forward counting rate. This is the expected signature for the microwave magnetic-resonance–induced depolarization of negative muons in $(^4He^{++}\mu^-e^-)^0$ which are spin polarized opposite to the beam direction.

Figure 3 shows the resonance signal of the hfs transition in $(^4He^{++}\mu^-e^-)^0$ as a function of the microwave frequency ν. Each datum point corresponds to about 20 h of data taking. The curve represents a least-squares–fit line shape, which is approximately a Lorentzian. The final result for the center of the resonance line is $\Delta\nu = 4465.216(56)$ MHz, which is the weighted average of separate fits to the forward and backward signals [$\Delta\nu_F = 4465.139(107)$ MHz with $\chi^2 = 0.90$ for 25 degrees of freedom, and $\Delta\nu_B = 4465.248(65)$ with $\chi^2 = 1.13$ for 25 degrees of freedom].

In order to determine the vacuum value of the muonic helium hfs splitting, a pressure-shift correction has to be applied to the frequency measured in the buffer gas at a pressure of 19.4 atm and a temperature of 22 °C. In our case, this correction could be deduced with sufficient accuracy from the muonium hfs transition $\Delta\nu(\mu^+e^-)$ (19.4 atm) = 4463.566(17) MHz in exactly the same target gas yielding the total pressure shift[7] for muonium

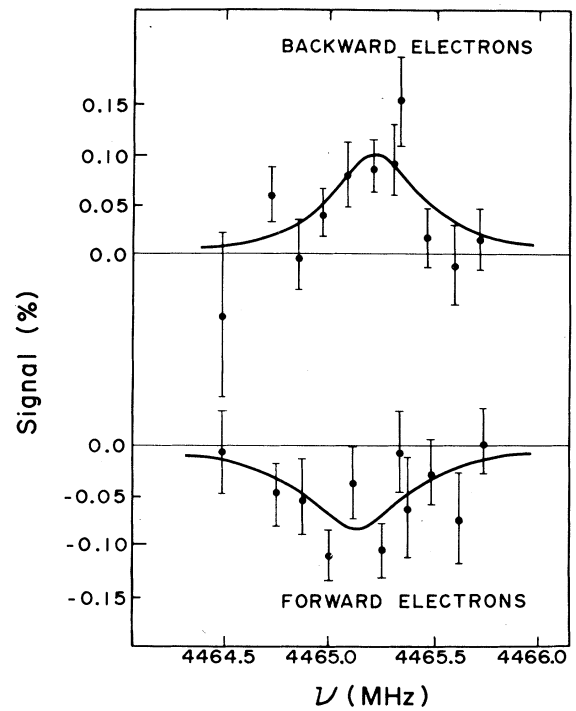

FIG. 3. Resonance curves for the $\Delta F = \pm 1$, $\Delta M_F = \pm 1$ hfs transitions in $(^4He^{++}\mu^-e^-)^0$, simultaneously observed in the backward (upper graph) and forward (lower graph) electron telescopes as a function of the microwave resonance frequency.

of $\delta(\Delta\nu) = 0.264(17)$ MHz. If we apply this correction, we arrive at our final result for the free muonic helium atom,

$$\Delta\nu((^4He^{++}\mu^-e^-)^0) = 4464.95(6)\ \text{MHz}.$$

The pressure-shift extrapolation is well justified for the presently attained precision in $\Delta\nu$ of ± 13 ppm, since the fractional hfs pressure shift is known to be very similar for muonium and for the three hydrogen isotopes in many rare gases.[14-16] The $(^4He^{++}\mu^-e^-)^0$ may be regarded as the next heavier isotope in this sequence.

Our experimental result is in good agreement with recent theoretical values[11,12] within the relatively large theoretical uncertainties. The precision in $\Delta\nu$ of this experiment (± 13 ppm) is given by statistics only. There are no major limitations on improving this result by more than an order of magnitude. Indeed, the data of an experiment at the Clinton P. Anderson Meson Physics Facility at Los Alamos,[17] in which Zeeman transitions at 11 kG in the $(^4He^{++}\mu^-e^-)^0$ ground state were observed, will probably reach an improved accuracy. It should also be possible to measure similar microwave magnetic-resonance transitions in $(^3He^{++}\mu^- e^-)^0$, in which the value of $\Delta\nu$ will be determined in part by the magnetic moment of the ^{3}He nucleus.[8]

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First-Passage-Time Distributions under the Influence of Quantum Fluctuations in a Laser

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The distribution of first-passage times is calculated for a homogeneously broadened two-mode laser, that is characterized by a bistable potential. As a consequence of quantum fluctuations, such a system tends to switch spontaneously between the two metastable states. The results of the calculation are compared with first-passage-time measurements of a two-mode dye laser.

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The behavior of a system subject to fluctuations under the influence of a double potential well, that provides two metastable states, is a fundamental problem in physics. Examples of such bistable systems can be found in fluid dynamics, thermodynamics, and quantum optics, and they are frequently associated with first-order phase transitions.[1] The problem of determining the rate at which the system switches between bistable states is the classic first-passage-time problem, which has been treated in numerous papers.[2,3] However, there appear to be few examples in which the probability distribution of the first-passage times can be easily calculated and compared with measurements. We wish to describe a simple physical system, a laser oscillating in

