We have assumed the point nuclear charge in Eq. (9). The effect of the finite nuclear size can be evaluated in a way described in the references.[5] A contribution of the pseudoscalar term in Eq. (4) is very small as is given elsewhere.[13]

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Hyperfine Structure of $2s$ $^3He^+$ by an Ion-Storage Technique*

M. H. Prior and E. C. Wang
Department of Physics and Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
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An electrostatic confinement device has provided resonance linewidths $\simeq 1$ kHz for the hyperfine transition $F=1$, $m_F=0$ to $F=0$, in metastable $2s$ $^3He^+$. The state-selection and resonance-detection scheme is the same used in an earlier ion-beam experiment; however, ion storage has yielded a resonance linewidth narrower by a factor of 100. Our result for the $2s$ hyperfine structure is $\Delta\nu_2 = 1083.354\,969(30)$ MHz. Comparison with the $1s$ hyperfine structure yields a test of state-dependent terms in the theory.

It is well known that in the theory of the hyperfine structure of atomic hydrogen, uncertainty in the size of the nuclear-structure correction limits its comparison with experiment to the level of about 3 ppm. This far exceeds the experimental precision of $\simeq 1\times10^{-6}$ ppm, and, for example, precludes a good test of the quantum-electrodynamic (QED) correction term proportional to $\alpha(Z\alpha)^2$ which is calculated[1] to be 2.27(62) ppm. It is possible, however, to reduce the importance of nuclear structure if one compares the hfs in the $2s$ and $1s$ states. In particular the quantity $D_{21} \equiv (8\Delta\nu_2 - \Delta\nu_1)$, where $\Delta\nu_2$ and $\Delta\nu_1$ are the $2s$ and $1s$ hfs, has a contribution in hydrogen due to the $\alpha(Z\alpha)^2$ term of about 2%, whereas the nuclear structure is not expected to contribute more than about 0.01%. The obvious drawback to this strategy is the requirement for two precision measurements.

In the case of $^3He^+$, in a unique and pioneering experiment, Novick and Commins[2] measured $\Delta\nu_2 = 1083.354\,99(20)$ MHz and, by a novel ion-storage technique, Schuessler, Fortson, and Dehmelt[3] measured $\Delta\nu_1 = 8665.649\,867(10)$ MHz. This yields $D_{21} = 1.1901(16)$ MHz. One sees that the uncertainty in $\Delta\nu_2$ is responsible for virtually all the uncertainty in D_{21}. It was the goal of the present work to determine $\Delta\nu_2$ more accurately. Our experiment uses the same method of state selection and resonance detection as the work of No-

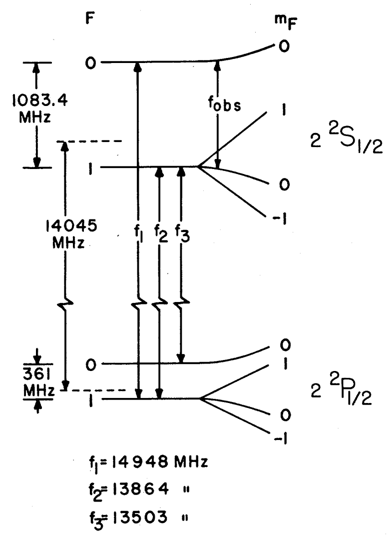

FIG. 1. Hyperfine and Zeeman levels of $^3He^+$ $2s$ and $2p_{1/2}$ states. The $2p_{1/2}$ state has a 10^{-10}-sec lifetime and emits a 304-Å photon in decay to the $1s$ ground state. The transition studied is marked f_{obs}.

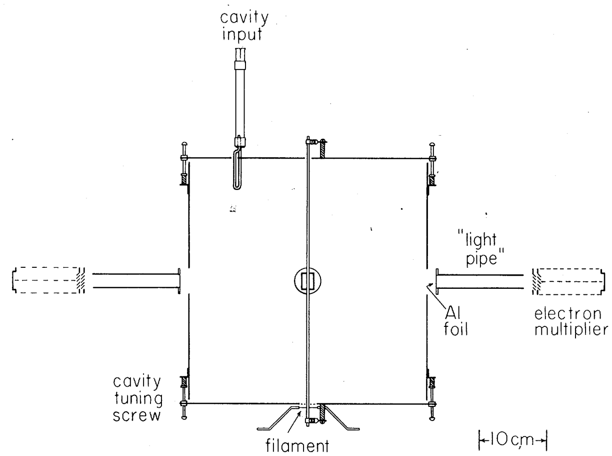

FIG. 2. Sketch of the electrostatic ion trap/rf cavity and photon detectors. The rod is maintained at a negative potential with respect to the closed cylinder during ion confinement. The rectangular shape shown behind the rod center is the microwave horn used to induce $2s$ to $2p_{1/2}$ transitions.

vick and Commins; however, our ion-storage technique has yielded a resonance linewidth about 1/100 of theirs.

Understanding of this work will be aided by reference to the $^3He^+$ energy-level diagram in Fig. 1. Metastable $^3He^+$ $2s$ ions are created by electron impact on ambient ^3He atoms at about 3.5×10^{-6} Torr pressure inside an electrostatic ion trap. Following excitation, the Lamb-shift transition $2s$ $F=1$ to $2p_{1/2}$ $F=0, 1$ is selectively induced via a 50-μsec pulse of $\simeq 250$ mW of microwave power at 13.3 GHz; this time interval is termed the A period. (13.3 GHz is not the peak of the Lamb-shift resonance but is optimal for state selection.) Ions which arrive in the $2p_{1/2}$ state immediately decay ($\tau_{2p} = 10^{-10}$ sec) to the $1s$ state emitting 304-Å Lyman-α photons. Following the A period one has an excess of $2s$ ions in the $F=0$ hyperfine level. During the C period, immediately following A, $F=0$ to $F=1$ hyperfine transitions are excited via application of a suitably polarized oscillating magnetic field at or near $\Delta\nu_2$, after which, in the 50-μsec B period, the microwave power is reapplied and induced Lyman-α photons are counted. A record of photons counted versus frequency applied during the C period yields a resonance curve. This scheme is the timelike analog of the ion-beam experiment of Novick and Commins, the advantage being that our C periods can be much longer (yielding a correspondingly narrower resonance) than the C-region transit time of their 20-eV ion beam. In this work we have used C periods ranging from $t_C = 0.4$ to 1.6 msec—equivalent to C-region lengths of 14 to 58 km. Our method allows a continuously variable C period; however, decay of the metastable ions and decreased duty cycle rapidly lower the count rate below acceptable limits in the current apparatus for $t_C \gtrsim 1.6$ msec. In favor of the ion-beam experiment was its high signal-to-noise ratio which allowed location of the resonance line center to 1/500 of its width ($\simeq 100$ kHz) whereas we have been limited to about 1/30 of our linewidth ($\simeq 1$ kHz); nonetheless a net gain in precision has been achieved.

Figure 2 shows a cross section of the ion trap; it is identical in principle to one used by Kingdon[4] in 1923 to study electron space-charge neutralization by trapped ions. It is a closed cylinder with a central rod maintained at a negative potential with respect to the grounded cylinder walls. Ions created by impact with electrons moving a few centimeters from the rod, and approximately parallel to it, orbit about the rod and oscillate along its length in the potential well created by the presence of the ends of the cylinder. The cylinder and rod also form a cavity resonant in the TE_{011} mode with a Q of about 1000 at a frequency nearly equal to $\Delta\nu_2$. The rod has a diameter of $\frac{1}{8}$ in. and the cylinder has an inside diameter of about 14 in. The trap is made of oxygen-free high-conductivity (OFHC) copper with alumina insulators and stainless-steel screws used for assembly and cavity tuning via adjustment of the cylinder length. The 13.3-GHz microwave power is broadcast into the trap volume by a horn aimed through a hole in one side of the cylinder, and is on-off modulated by a p-i-n-diode switch.

The two photon detectors are eighteen-stage CuBe Venetian-blind electron multipliers viewing the trap through internally gold-plated light pipes and thin (800-Å), 18-mm-diam, aluminum foils. The foils stop metastable neutral atoms (He $2\,^1S_0$, $^3S_1$) from reaching the multipliers.

The entire device is enclosed in an evacuated stainless-steel chamber. The base pressure during these measurements was typically 5×10^{-8} Torr. ^{3}He is admitted to the chamber through a micrometer-controlled valve set to maintain $\simeq 3.5\times 10^{-6}$ Torr pressure during data collection.

Power to excite the hfs resonance is introduced into the ion trap cavity by a coaxial vacuum feed-through and coupling loop inserted into the cylinder as shown in Fig. 2. To obtain the 1083 MHz required, the output frequency of a Hewlett-Packard 5105 frequency synthesizer is quadrupled; the product enters a p-i-n-diode absorptive modulator which passes it into the cavity only during the C period. The synthesizer frequency ($\simeq \Delta\nu_2/4$) is controlled digitally by the data-collection system and is swept repetitively across the hfs resonance.

The experiment is controlled by a data-collection system which stores counts received during the B period versus frequency in 100 channels of a multichannel scaler (MCS). A typical data cycle consists of a 0.1-msec fill period, during which 200-eV electrons are injected into the trap, followed by the A, C, and B periods and a 50-μsec dump period during which the rod potential is brought up to ground to allow ions to escape. The entire cycle then takes 0.65 to 1.85 msec, depending on t_C. Usually counts from 1000 data cycles are stored in each channel before changing the synthesizer frequency. The 100 channels of the MCS are repetitively scanned to allow buildup of a resonance signal. Depending on conditions, this may take from 15 min to a few hours to achieve a signal-to-noise ratio of $\simeq 25{:}1$.

We observe the $F=0$ to $F=1$, $m_F=0$ hyperfine transition in a weak magnetic field. This transition has the field dependence $f\,(\mathrm{MHz}) = \Delta\nu_2 + (3.615\times 10^{-3})H^2$, where H is in gauss. We generate H with three sets of Helmholtz coils. One pair produces a field parallel to the trap axis (z axis) and the remaining two, fields along orthogonal axes (x, y) normal to the trap axis. H_x and H_y are adjusted separately to zero by minimizing f in the presence of a small but finite H_z (e.g., 0.5 G). (H_z establishes a quantization axis, parallel to the TE_{011} magnetic field, required to excite the $\Delta m_F=0$ transition.) Figure 3 shows examples of resonance curves obtained at a fixed $H_z \simeq 0.56$ G for various values of t_C.

Resonance curves are then collected for several values of I_z, the current in the z-axis pair, spanning the range $\simeq \pm 0.8$ G. The resonance curves are least-squares fits by a computer with the function

$$S(f) = AL(f)\sin^2(\pi t_C BL(f)^{-1/2}) + C, \qquad (1)$$

where $L(f) = B^2/[B^2 + (f - f_z)^2]$. This yields the parameters A, B, C, and the line center f_z. The data f_z versus I_z is then fitted with the form $f_z = f_0 + K(I_z - I_0)^2$ yielding K, I_0, and f_0. I_0 is nonzero due to the ambient H_z in the laboratory. Typically six values of I_z are used to make one determination of f_0 and this requires about 1 day of data collection.

Several small systematic corrections are applied to f_0 to determine a value for $\Delta\nu_2$. The

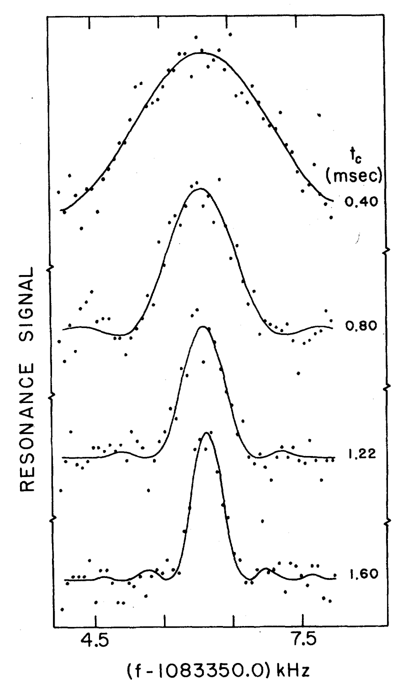

FIG. 3. Resonance curves taken at a field of $H_z \simeq 0.56$ G with differing values of t_C. The solid lines are computer fits to the data. The resonance amplitude is typically 20% of the baseline.

largest systematic correction is the compensation for the frequency offset of the synthesizer internal standard versus the national frequency standard as received from WWVB. This amounted to from 30 to 40± 1 Hz during the course of the measurements. One also could expect a small Stark shift in $\Delta\nu_2$ due to the electric field in the trap. An experimental search for such an effect was made by operating the trap at rod potentials varying between − 3.0 and − 16.0 V; no large effect was observed. This is consistent with our resolution and calculated estimates of the mean-square electric field seen by the $^3He^+$ ions ($\simeq 1.0\ V^2/cm^2$ for most runs). To the mean value of all runs we have applied a correction of − 15± 15 Hz to include a possible Stark shift. A positive correction of +5± 5 Hz was made to the data to account for estimated residual x and y magnetic fields and for inhomogeniety in H_z.

Our final result is then $\Delta\nu_2 = 1083.354\,969(30)$ MHz; the uncertainty is primarily the result of the 25-Hz standard deviation of a single measurement from the mean of 26 values. The result is in agreement with that of Novick and Commins and has an uncertainty of about a factor of 7 smaller. We obtain $D_{21}(\text{expt}) = 1.189\,89(24)$ MHz. The theoretical value $D_{21}(\text{theor}) = 1.189\,77$ MHz is the sum of contributions of 1.152 94 MHz from the Breit correction through order $Z\alpha$,[4] 0.036 03 MHz from QED corrections[5,6] proportional to $\alpha(Z\alpha)^2$ and $\alpha(Z\alpha)^2\ln(Z\alpha)$, and 0.000 80 MHz from second-order hyperfine structure and nuclear-recoil effects.[7,8] The precision of the agreement between D_{21}(theor) and D_{21}(expt) limits the net effect of state-dependent hfs correction terms not included in D_{21}(theor) to ± 0.02%. The previous limit, using the Novick and Commins value for $\Delta\nu_2$, was ± 0.14%. If one singles out the QED contributions to D_{21}, our new result shows agreement with the net effect of the $\alpha(Z\alpha)^2\ln(Z\alpha)$ terms to the level of ± 0.66%. The case of atomic hydrogen and deuterium is less favorable due to the Z dependence of D_{21} and the precision of the $\Delta\nu_2$ measurements (± 0.3 ppm for H and ± 0.5 ppm for D.[9,10] For hydrogen, agreement with the QED contribution is at the level of ± 19%. We plan to improve the apparatus and further reduce the uncertainty in $\Delta\nu_2$ for $^3He^+$ using this method.

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