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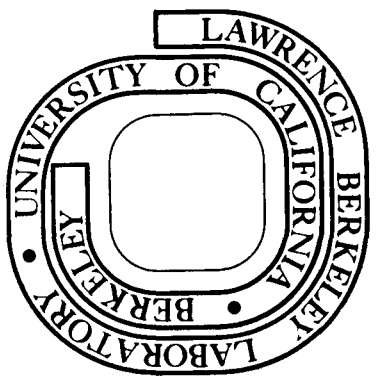


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## DISCLAIMER

# HYPERFINE STRUCTURE OF 2s $^3He^+$ *

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## ABSTRACT

An electrostatic confinement device has provided resonance line widths ≈ 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 identical to that used in the ion-beam experiment of Novick and Commins. Our result for the 2s hyperfine structure is $\Delta\nu_2$ = 1083.354978(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 (hfs) of atomic hydrogen, uncertainty in the size of the nuclear structure correction limits comparison with experiment to the level of about three parts per million (ppm). This far exceeds the experimental precision of $\simeq 1 \times 10^{-6}$ ppm, and, for example, precludes a good test of the quantum electrodynamic 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 .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 $\Delta\nu_2$ = 1083.35499(20) MHz and, by a novel ion storage technique, Schuessler, Fortson and Dehmelt[3] measured $\Delta\nu_1$ = 8665.649867(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 improve $\Delta\nu_2$.

Our experiment uses the same method of state selection and resonance detection as the work of Novick and Commins. Figure 1 shows an energy level diagram of $^3He^+$ relevant to this work.

Metastable $^3He^+$ 2s ions are created by electron impact on ambient $^3He$ atoms at about $3.5 \times 10^{-6}$ 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 ≈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 time-like 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$100 kHz) whereas we have been limited to about 1/30 of our line width ($\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 1/8 inch and the cylinder has an inside diameter of about 14 inches. The trap is made of OFHC copper with allumina 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 pin-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 diameter, 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 $5 \times 10^{-8}$ 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 feedthrough and coupling loop inserted into the cylinder as shown in Figure 2. To obtain the 1083 MHz required, the output frequency of a Hewlett-Packard 5105 frequency synthesizer is quadrupled; the product enters a pin-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 .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 microsec 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 build up of a resonance signal. Depending on conditions, this may take from 15 minutes to a few hours to achieve a signal-to-noise ratio of ≃ 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 $f(\text{MHz}) = \Delta\nu_2 + 3.615 \times 10^{-3} H^2$ 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. .5 gauss). ($H_z$ 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 $H_z \simeq .56$ gauss 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 ≃ ±.8 gauss. The resonance curves are least squares fit by a computer to the function:

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

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 fit to the

form $f_z = f_o + K(I_z - I_o)^2$ yielding K, $I_o$ and $f_o$. $I_o$ is non-zero due to the ambient $H_z$ in the laboratory. Typically 6 values of $I_z$ are used to make one determination of $f_o$ and this requires about one day of data collection.

Several small systematic corrections are applied to $f_o$ to determine a value for $\Delta\nu_2$. The 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 volts; 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 $\Delta\nu_2$ = 1083.354978(30) MHz, the uncertainty is primarily due to 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 about a factor of

7 smaller uncertainty. We obtain $D_{21}(\text{exp}) = 1.18996(24)$ MHz. The theoretical value $D_{21}(\text{th}) = 1.18977$ MHz is the sum of contributions of 1.15294 MHz from the Breit correction through order $(Z\alpha)^4$, .03603 MHz from QED corrections[5, 6] proportional to $\alpha(Z\alpha)^2$ and $\alpha(Z\alpha)^2 \ell n(Z\alpha)$, and .00080 MHz from second order hyperfine structure and nuclear recoil effects.[7, 8] The difference $D_{21}(\text{exp}) - D_{21}(\text{th}) = 0.00019(24)$ MHz indicates the smallness of state dependent terms not included in the hfs theory. It is interesting to note that the $\alpha(Z\alpha)^2$ contribution to $D_{21}(\text{th})$ is some 100 times the uncertainty in $D_{21}(\text{exp})$ whereas the analogous term in the Lamb shift is about equal to the experimental uncertainty.[9] We plan to improve the apparatus and further reduce the uncertainty in $\Delta\nu_2$ using this method.

We wish to extend our gratitude to Dr. Peter J. Mohr for many helpful discussions regarding the theoretical aspects of this work.

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* Work supported by the U. S. Atomic Energy Commission.

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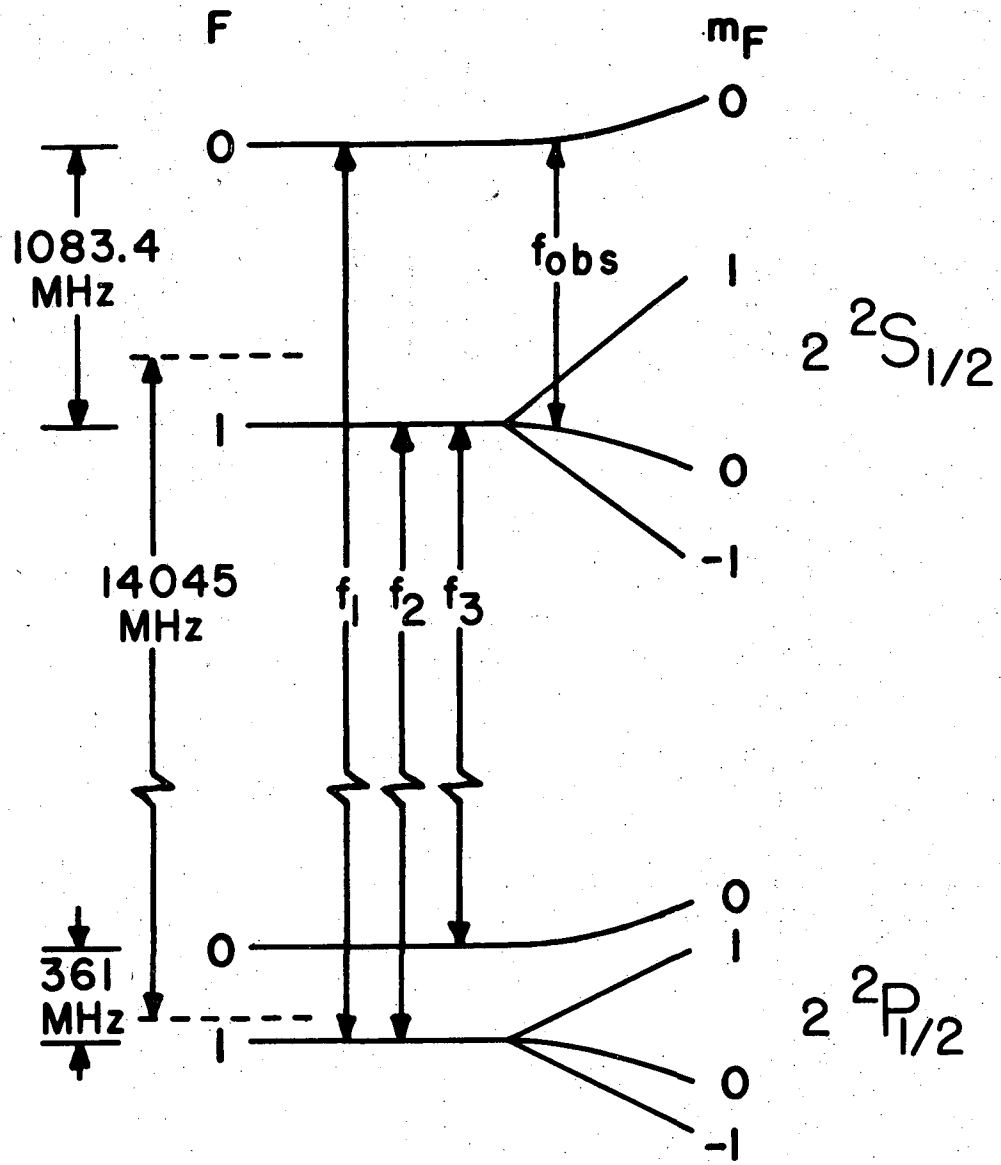
## FIGURE CAPTIONS

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.

Fig. 3 Resonance curves taken at a field of $H_z \simeq .56$ gauss with differing values of $t_c$. The solid lines are computer fits to the data. The resonance amplitude is typically 20% of the baseline.




$f_1 = 14948$ MHz

$f_2 = 13864$ "

$f_3 = 13503$ "

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Fig. 1

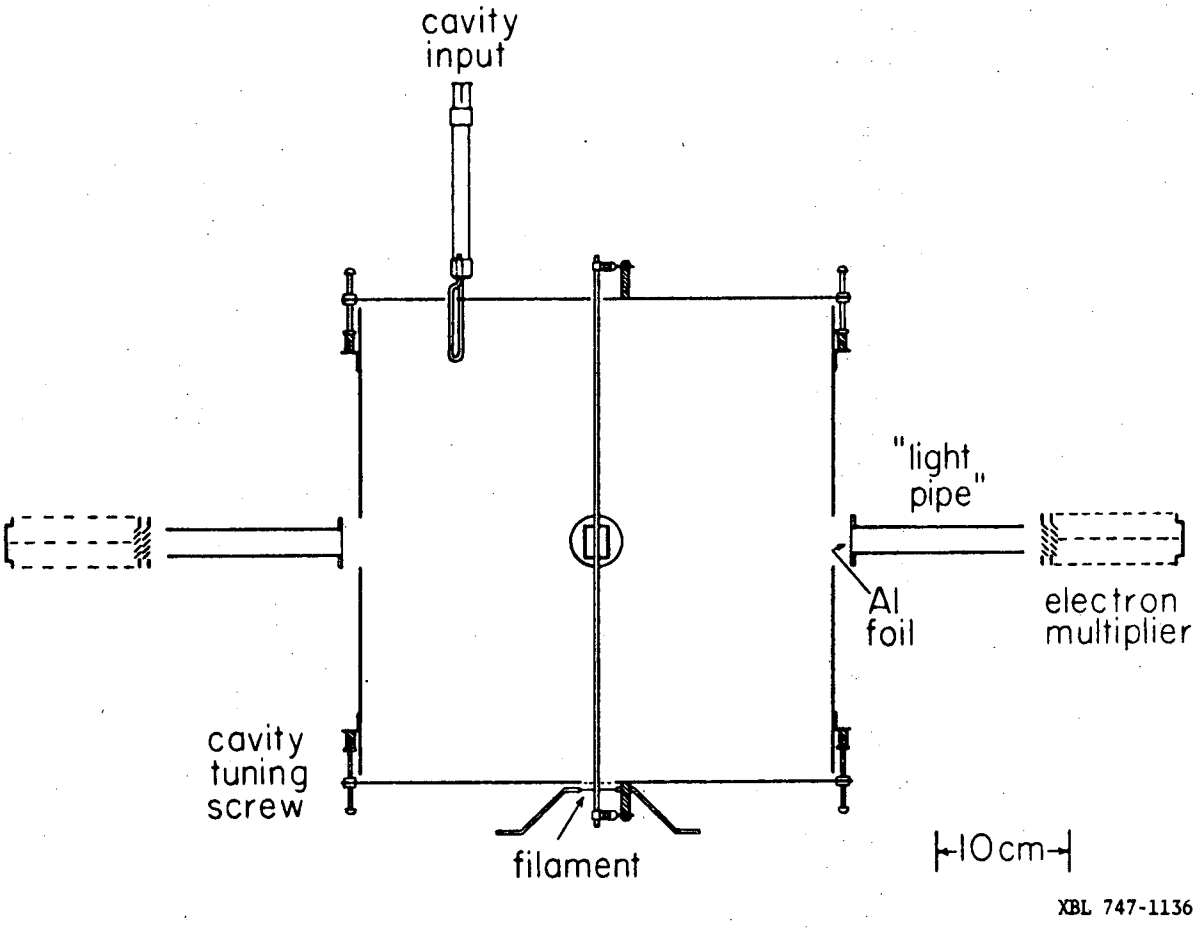
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Fig. 2

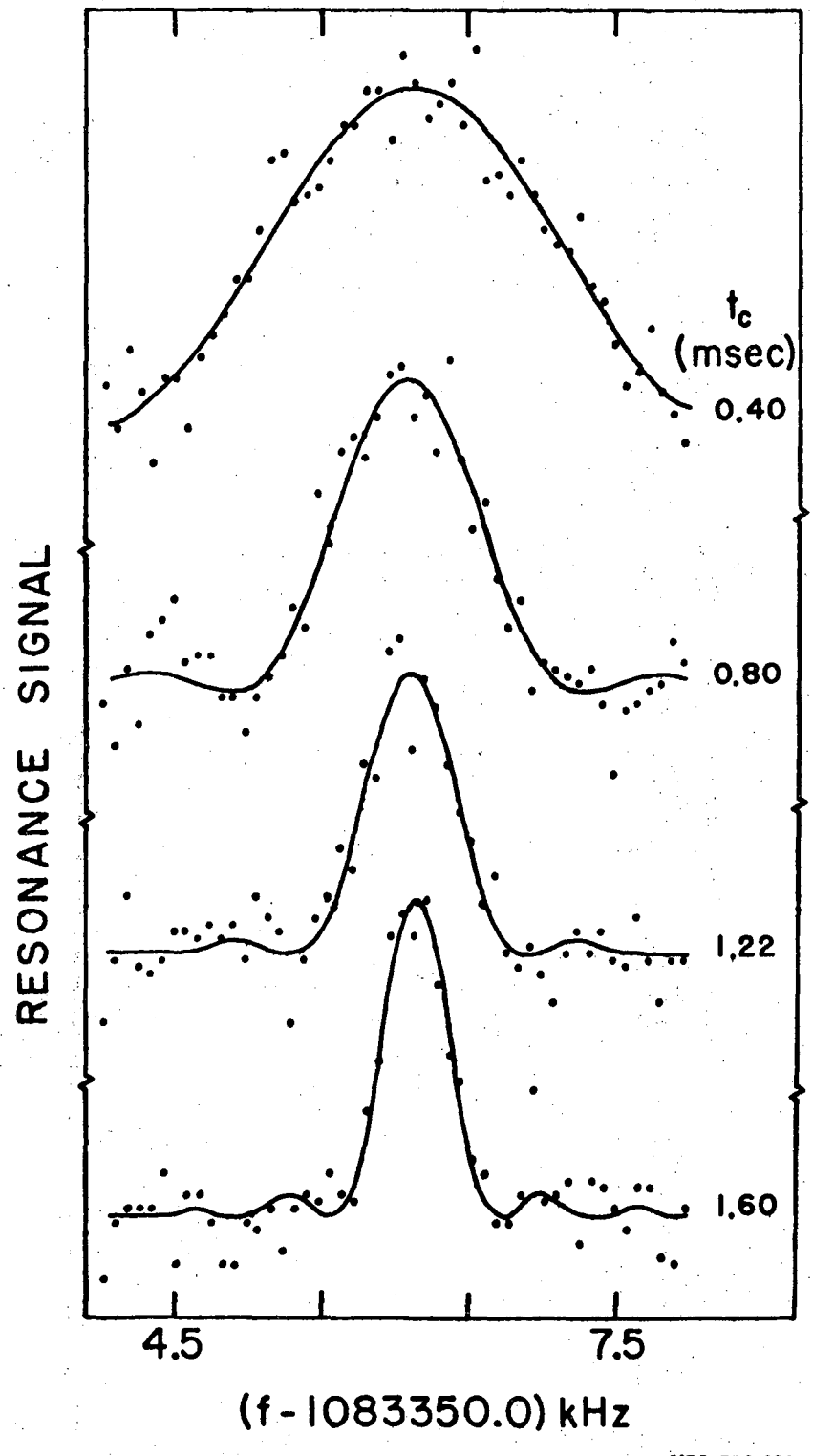


Fig. 3

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