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Author
Prior, M.H.

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M. H. Prior

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Lifetime of the 2 S State of He$^+$ [†]

M.H. Prior
Lawrence Berkeley Laboratory
Berkeley, California 94720

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ABSTRACT

The lifetime of the 2 S state of He$^+$ has been measured by counting decay photons versus time from an ensemble of excited He$^+$ ions stored in an electromagnetic trap of the Penning type. The result is τ_{2S} = 1.922 (82) msec. This is in agreement with the theoretical value of 1.899 msec. The agreement between theory and experiment implies a new upper limit on the amount of parity impurity in the 2 S wave function.

Pioneering experiments[1] by workers at Columbia University established conclusively that the radiative decay 2 S to 1 S in He^+ proceeds via spontaneous two photon emission. This is in strict accord with theory[2] which forbids single photon electric dipole (E1) radiation by parity conservation, and predicts a single photon magnetic dipole (M1) rate $\approx 5 \times 10^{-6}$ times smaller than that for emission of two E1 photons. Recently Marrus and Schmieder have reported[3] measurements of the 2 S lifetime, τ_{2S}, in hydrogen-like Ar^{+17} and S^{+15} by a beam-foil time-of-flight technique. However, except for the establishment of lower limits in H (Ref. 4) and He^+ (Ref. 5), an experimental value for τ_{2S} in a low Z ion has not been reported.

This letter describes work carried out to determine τ_{2S} in He^+. The results are in agreement with the theoretical value[6] of 1.899 msec and lead to a new upper limit on the amount of parity impurity in the 2 S state wave function in He^+.

The 2 S state lies 40.8 eV above the He^+ 1 S ground state, hence the two photons emitted must have energies such that $h\nu_1 + h\nu_2 = 40.8$ eV. The single photon distribution with wave length is then a continuous one with a short wavelength cut off at $\lambda_{min} = 304$Å and extending to infinite wavelength. The distribution rises rapidly from λ_{min} to a peak at ≈ 350Å after which the intensity falls off roughly as $\exp[-(\lambda - 350)/430]$.

The method used to measure τ_{2S} is basically the same as that used[7] to measure the lifetime of the $n = 2\ {}^1S_0$ state in Li^+. A quantity ($\approx 10^2$) of He^+ 2 S ions are created by pulsed electron impact on He gas ($p \approx 10^{-7}$ Torr) at time $t = 0$. The ions are confined inside an ion trap for a period of several lifetimes (typically 8 msec). During this storage time, single decay photons are detected by windowless electron multipliers and the resulting pulses are stored vs. time in 100 channels of a multichannel scalar (80 μsec/channel). At the end of the storage period, all ions are dumped from the trap and a new cycle is begun. Many fill-store-dump cycles are repeated until a decay curve is built up which has sufficiently small statistical error to allow determination of a value for τ_{2S}. (This may take from 15 min to 2 hours depending on the experimental conditions.)

An important consideration in any experiment to measure the lifetime of He^+ 2 S is the nearness of the 2 $P_{\frac{1}{2}}$ state, the separation being the Lamb shift $S \approx 14.045$ GHz. The radiative lifetime of the 2 $P_{\frac{1}{2}}$ state is $\tau = 10^{-10}$ sec. Hence, any perturbation which mixes 2 S and 2 $P_{\frac{1}{2}}$ can drastically affect (quench) the 2 S state. In particular, an electric field E will cause mixing via the Stark effect, and yield an effective lifetime τ' given by

$$\tau' = \tau_{2S}\,\tau_P/(\tau_P + b^2\tau_{2S})$$

where

$$b^2 = \frac{(4\pi\tau_P)^2\ |M|^2}{1 + (4\pi\tau_P hS)^2} \qquad \text{and } M = \sqrt{3}eEa_0/Z \quad .$$

For He^+ $b = 7.87 \times 10^{-5}$ E (V/cm) and hence electric fields less than 1.0 V/cm are required if τ' is to be within 10% of the field free value τ_{2S}. Magnetic fields will also cause quenching via the motional electric field $\underset{\sim}{E}_m = \underset{\sim}{v}/c \times \underset{\sim}{B}$; e.g. for $v = 2.5 \times 10^5$ cm/sec, $E_m < 1.0$ V/cm for $B < 400$ gauss. For these reasons the ion trap operates with rather low magnetic (≈ 50 gauss) and electric fields (≈ 0.1 V/cm). Weak fields will not confine ions to small volumes, which explains the large size of this ion trap ($\approx 2 \times 10^4$ cm^3) compared to a similar trap (≈ 10 cm^3) used in the work[7] on Li^+.

Figure 1 shows the ion trap and photon detectors. The ion trap is a closed cylinder (radius ≈ 15 cm, length ≈ 30 cm) whose ends are maintained at a positive potential with respect to the body; potentials used range from 0.5 to 3 volts. A magnetic field from 40 to 65 G is applied coaxial with the cylinder by means of coils external to the vacuum enclosure. The electrostatic field confines ion motion along the magnetic field, while the magnetic field limits motion perpendicular to the trap axis.

The trap is constructed primarily from OFHC copper, stainless steel, and alumina insulators, and the vacuum enclosure is entirely of stainless steel. After bake-out, pressures of $< 2 \times 10^{-9}$ Torr were achieved and during data collection the background gas pressure is always less than 5×10^{-8} Torr. Helium gas is admitted to the chamber containing the trap via a micrometer needle valve which allows varying the He pressure to study the effects of collisional quenching on the 2 S decay rate.

Helium ions are created in the trap by impact from an electron pulse accelerated along the axis of the magnetic field. Typically the electron pulse is 100 μA, lasts .75 msec, and has an energy of 225 eV. At a helium pressure of 1.7×10^{-7} Torr this yields about 2×10^{5} ions, of which approximately 200 can be expected to be in the 2 S metastable state. At the end of a storage period the trap potentials are altered so that ions are dumped onto a collecting plate (electrode 4 in Figure 1); this allows monitoring of the number of stored ions via the size of the resulting positive current pulse. The electron pulse also appears on this electrode during the trap fill time.

As is indicated in Figure 1, the cylindrical portion of the trap is made up of two half cylinders 2a and 2b; this allows application of an alternating potential between them (while maintained at a common dc potential) which can excite resonant motion of the stored ions at their cyclotron frequency. At resonance the ions gain energy from the ac field until they strike the electrodes or chamber walls; thus one observes a drop in the ion dump pulse amplitude when the applied frequency is in resonance. In addition to the cyclotron resonance one observes resonance at the frequency of motion along the trap axis (z - motion) and at the magnetron frequency (frequency of drift of the cyclotron orbit center about the trap axis).

The photon detectors are two EMI 9642/2 eighteen-stage CuBe venetian-blind electron multipliers. To prevent metastable helium atoms ($2\ ^3S_1$ and $2\ ^1S_0$) from reaching the multipliers, their view of the storage volume is covered by aluminum foils 18 mm in diameter and 800 Å thick. The foils have a transmission varying between 10 and 70% over the region 200 to 700 Å. The Al foil-CuBe multiplier combination respond to ≈ 2% of the radiation over the range 300 to 500 Å which strikes the Al foil. The two light pipes are Pyrex tubes coated internally with a 1000 Å thickness of gold; they enhance the count rate by about a factor of four over the case with no light pipes.

To establish that the observed decay is that from He^+ 2 S, microwave power (≈ 150 mW) at the Lamb shift frequency (14.045 GHz) is broadcast into the trap volume via a waveguide horn. This converts a large fraction (more than 80%) of the 2 S ions to the $2\ P_{\frac{1}{2}}$ state from which they immediately decay, destroying the 2 S decay curve. Measurement of the quenching versus microwave frequency yielded a Lamb shift resonance curve. The microwave power is generated by a Varian X-12 klystron and may be on-off modulated via a PIN-diode switch under control of the data collection logic system.

One typical data cycle consists of the following sequence: a .75 msec fill period during which time the electron pulse is on, a delay period of .8 msec during which the microwave power may or may not be applied, a storage period of 8 msec during which counts from the multipliers are accumulated versus time in 100 channels of the memory unit, and a 75 μsec ion dump period. Data is stored in two separate 100 channel blocks of the memory unit corresponding to whether or not microwave power is on or off during the delay period. Usually the microwave power is switched on or off every 5000 data cycles. The time base for the system is derived from a 100-kHz crystal oscillator.

Figure 2 shows a decay curve representative of those used to determine τ_{2S}. The data is the difference between counts accumulated with microwave power on and off. Each point is the sum of three 80 μsec. channels. The ratio of total counts with power off to power on was about 6:1. About 90 min were required to collect this data. The straight line through the points is the least squares fitted exponential decay curve which yielded $\tau = 1.866$ msec.

The final result is based on a total of 19 runs similar to that shown in Figure 2. During these runs the trapping potential was .9V, the magnetic field was 42.5 gauss and the He pressure was $\approx 1.7 \times 10^{-7}$ Torr. The mean value of the 19 run set is 1.864 msec. with a standard deviation for a single run from the mean of .079 msec. The mean value must be corrected slightly to allow for collisional and field quenching.

The effect of collisional quenching was studied by varying the He pressure up to a maximum of $\approx 5.5 \times 10^{-6}$ Torr. The resulting plot of τ^{-1} versus pressure yielded a positive correction of .035 msec to be added to the mean of the 19 runs.

The effect of quenching by the trap fields is taken into account by considering a hypothetical worst case. The maximum kinetic energy of a trapped ion was ≈ 1.0 eV (the trapping potential plus the maximum recoil energy) this corresponds to a velocity of 7×10^5 cm/sec. In a 42.5 gauss magnetic field this yields as a maximum motional electric field $E_m = .28$ V/cm. A good estimate of the maximum static electric field in the trap is given by

$$E_s = \frac{M}{q} A_z \ (2\pi f_z)^2$$

where M is the ion mass, q the ion charge and A_z and f_z are the amplitude and frequency of the z-motion. For He^+ ions with $A_z = 15$ cm, and the observed $f_z = 12.2$ KHz, one obtains $E_s = .37$ V/cm. Combining E_s and E_m vectorially yields $E = .46$ V/cm as a worst case estimate of the maximum electric field seen by an ion in the trap. This would produce a quenching effect of 2.5% on the 2 S lifetime. To account for field quenching then, we assume a positive correction of 1.25% (.023 msec) and include the same amount in computing the uncertainty in the result.

The final result is then $\tau_{2S} = 1.922$ (82) msec. The uncertainty is the quadrature sum of the .079 msec standard deviation of the 19 run distribution and the .023 msec uncertainty in the field quench correction.

The agreement between experiment and theory implies a limit on the amount of 2 $P_{\frac{1}{2}}$ state that may be mixed with 2 S by a hypothetical parity violating neutral weak current and/or electromagnetic interaction.[8-10] Thus, if the wave function is written $\psi(2S) = \phi(2S) + \epsilon\phi(2P_{\frac{1}{2}})$ with the ϕ's Schrodinger wave functions, the uncertainty in the result quoted here for τ_{2S} implies $|\epsilon| < 4.7 \times 10^{-5}$. This is an improvement by a factor of 10 over a previous limit based on τ_{2S} in Ar^{+17} (Ref. 3).

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Figure Captions

Figure 1. Sketch of the ion trap and photon detectors. The magnetic field is along the trap axis. The half cylinders 2a and 2b are maintained negative with respect to electrodes 1 and 3 during the storage period. Hot filament F is pulsed negative to accelerate electrons into the trap for creation of the He ions. The zig-zag pattern is a web of thin copper wires to give high transparency for the decay photons, while maintaining the cylindrical electrode geometry. The rectangular shape in the center of the figure represents the end of the microwave horn located outside the cylinder. Power radiated from this horn drives the 2 S to 2 $P_{\frac{1}{2}}$ transition.

Figure 2. A representative He^+ 2 S decay curve. The line is a computer fit which gave $\tau = 1.866$ msec. The final result is a corrected mean value derived from 19 such runs.

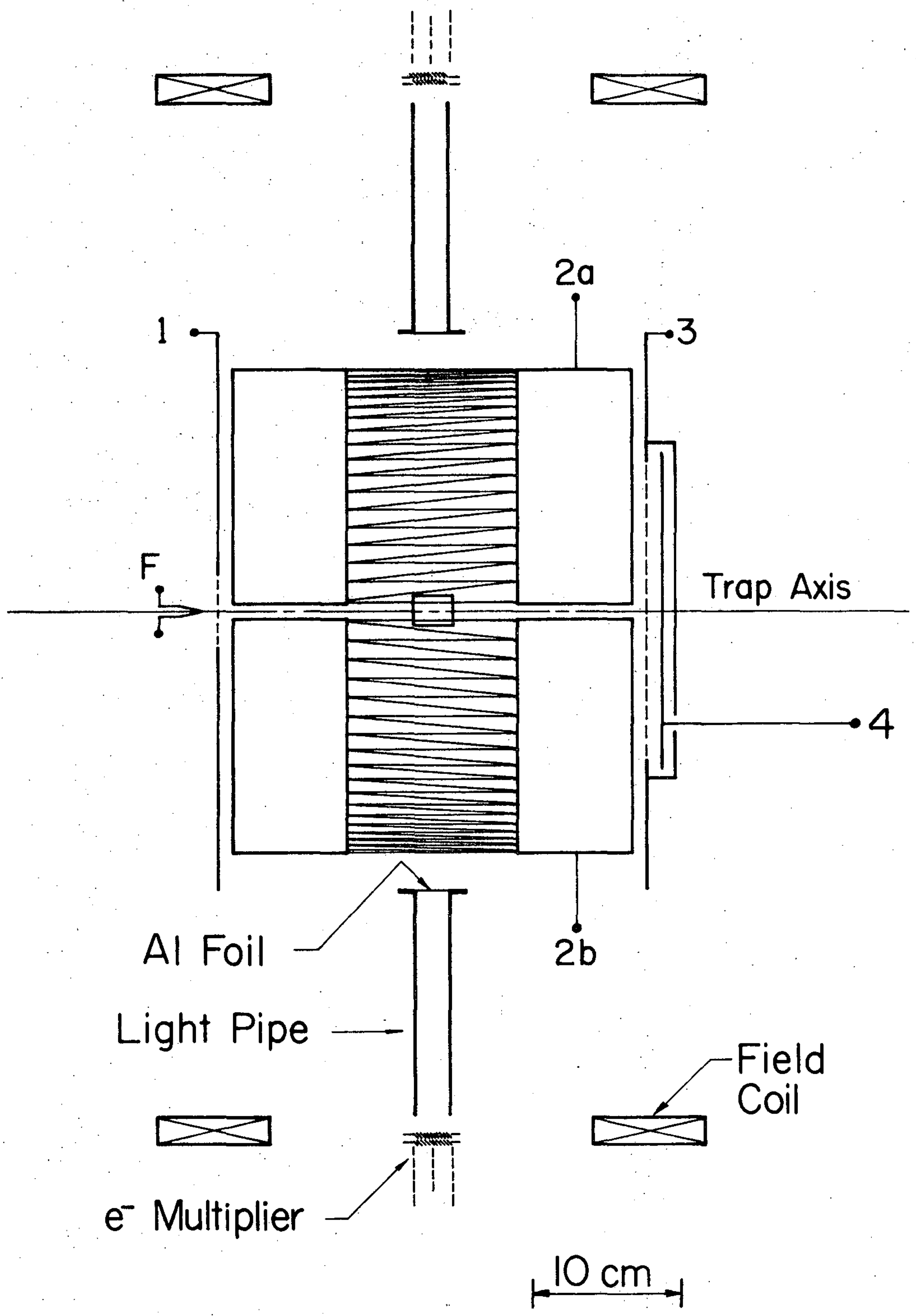

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Fig. 1

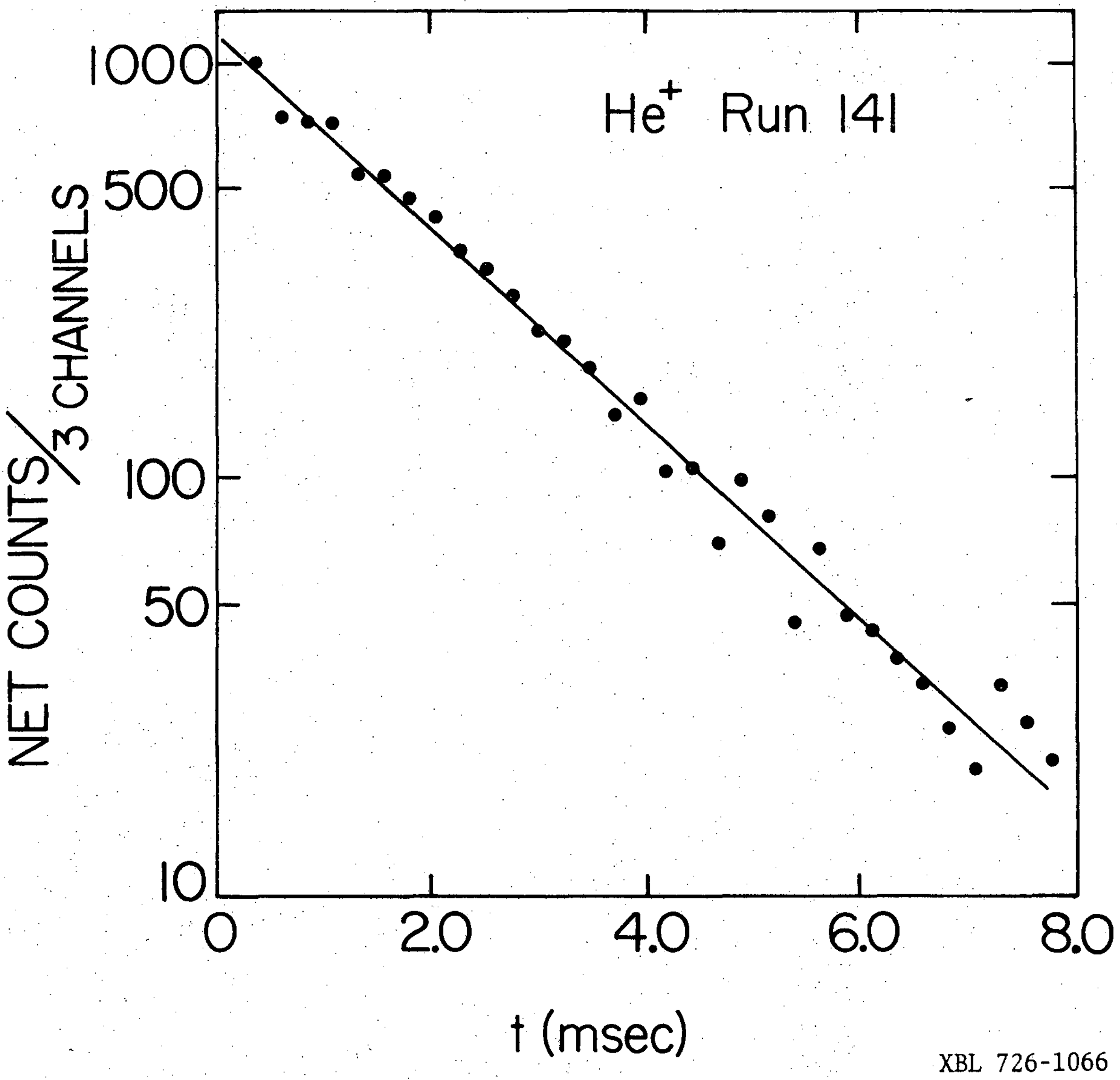

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Fig. 2

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720