Lifetime of the $2^2S_{1/2}$ State of Singly Ionized Helium*

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The natural lifetime of the $2S$ state of He^+ has been measured in a decay-in-flight experiment. The result, $\tau = 2.04^{+0.81}_{-0.34}$ msec, is consistent with the theory of two-photon spontaneous emission and determines an upper bound $\lambda \leq 8 \times 10^{-5}$ for the coupling constant of the pseudoscalar "anapole" interaction.

In this Letter we report a measurement of the lifetime of the $2S$ state of the hydrogenic helium ion. The metastability of this state and its proximity to the short-lived $2P$ state allow one to test for the presence of parity-nonconserving terms in the Hamiltonian for one-electron atomic systems. In the absence of such terms, this state decays with the simultaneous emission of two photons at a rate Γ_{theor} and lifetime τ_{theor} given by[1]

$$\Gamma_{\text{theor}} = 8.228 Z^6 \text{ sec}^{-1}, \qquad \tau_{\text{theor}} = 0.1215 Z^{-6} \text{ sec}. \tag{1}$$

For He^+, Feinberg[2] estimates that the radiative corrections to this result will be no more than a few percent. Relativistic corrections to the two-photon decay rate of order $(\alpha Z)^2$ have not been evaluated, but they are not expected to be important. Single-photon $M1$ decay is permitted by relativistic effects, but at a rate smaller than the two-photon rate by a factor of 10^6.

A preliminary estimate of the $2S$ lifetime in He^+ was obtained in 1962 by a decay-in-flight technique.[3] Later the two-photon emission was established in a photon-coincidence-counting experiment, and the angular correlation of the coincident photons was observed.[4] In addition, the gross features of the two-photon spectrum have been studied.[5] A review of the properties of the metastable hydrogenic atom has been published elsewhere.[6]

If a parity-nonconserving interaction were present, the $2P$ state would be mixed with the $2S$ state, permitting a first-order $E1$ transition and increasing the single-photon decay rate. Such a term could arise from an electronic or nuclear electric dipole moment or from an "anapole" or "pseudocharge" current.[7,8] Electric dipole moments require both T and P noninvariance, and the experimental limits[9] preclude any observable effect in the present experiment. Sakitt and Feinberg[8] have shown that an anapole interaction implies a single-photon $2S$ decay rate given by

$$\Gamma_a = \Gamma_{2P}(\lambda\sqrt{3} Z^5 \alpha^3 / 8\mathcal{S})^2, \tag{2}$$

where Γ_{2P} is the $2P$ decay rate, $\mathcal{S}$ is the Lamb-shift energy in atomic units, and λ is a dimensionless constant measuring the strength of the anapole interaction. At present there is no experimental evidence for the anapole interaction. Recently, Marrus and Schmieder[10] measured the two-photon decay rate for the $2S$ state of hydrogenlike Ar^{+17}, obtaining a result in agreement with the nonrelativistic two-photon theory and computing an upper limit $\lambda \leq 7 \times 10^{-5}$. This result may be modified when the relativistic and radiative corrections to the two-photon decay rate are evaluated.

In our experiment metastable ions are produced by electron bombardment of helium gas, then focused electrostatically into a beam and injected into a drift tube, where the decay in flight is observed by means of a traveling detector (Fig. 1).

The electron-bombardment ion source is of the type described by Dworetsky *et al.*,[11] with a Philips type-B impregnated cathode operating at an emission current of about 60 mA. The emitted electrons, accelerated to 200 eV, ionize and excite helium atoms within the anode cage of the source, where the density is approximately 10^{14} cm^{-3}. Electrostatic focusing maintains the collimation of the beam as it passes through a differential pumping chamber and enters the drift tube, 8 m in length. Typically the beam energy is 15 eV, and the final ion current is 5×10^{-8} A. About 0.5% of the ions are in the $2S$ state.

The detector consists of a molybdenum plate, 13 cm in diameter, preceeded by a pair of grids, both of which are normally grounded to the chamber. In an Auger-type process, secondary electrons are released from the detector plate as He^+ ions strike the metal surface. Consequently, the observed current is a sum of the incoming ion current and the outgoing current due to secondary electrons. A bias potential of -25 V on the de-

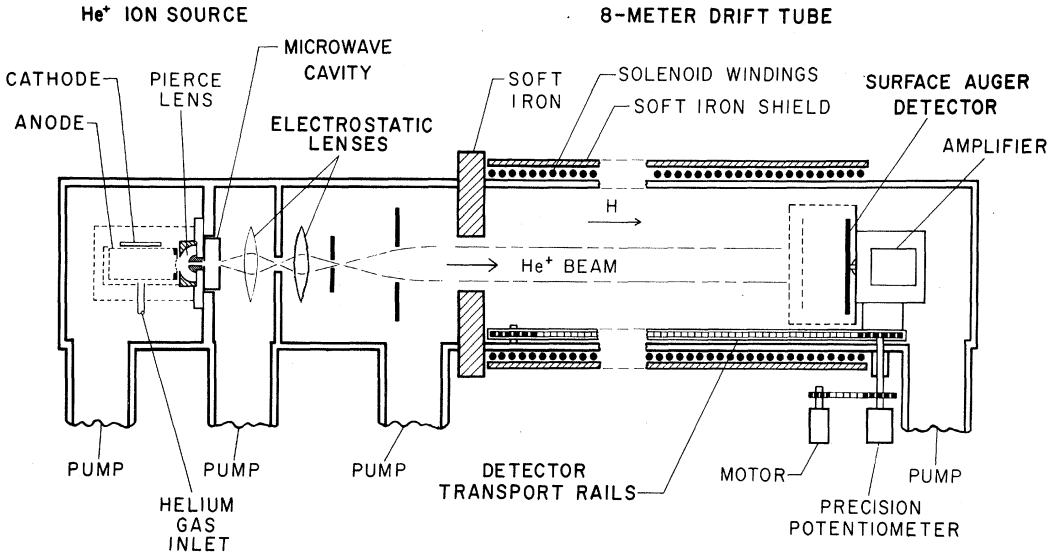

FIG. 1. Schematic diagram of the apparatus.

tector plate ensures that the secondary electrons are accelerated away from the plate. A metastable ion, having 40 eV of internal energy with respect to the ground state, is found to have a larger secondary electron probability (0.8) than a ground-state ion (0.3).[12] Modulation of the $2S$ population in the beam therefore results in a corresponding ac signal at the detector, superimposed on the dc signal due to the total ion current. This modulation is accomplished as the ions pass through a 14-GHz microwave cavity driven on-resonance by a klystron square wave modulated at 27 Hz. The microwave field, near the Lamb-shift frequency, strongly couples the $2S$ and $2P_{1/2}$ states, effectively quenching the metastable ions. A 27-Hz metastable current contribution of approximately 10^{-10} A is observed at the detector plate.

The direct and alternating currents are amplified by an Analog Devices 310K Varactor-bridge operational amplifier with a 10^8-Ω feedback resistance, mounted with the detector on a continuously movable platform. This arrangement offers a distinct advantage over a series of detectors at fixed positions, which may have differing Auger electron yields. The metastable ion signal is fed into a PAR model HR-8 lock-in amplifier followed by a logarithmic-ratio amplifier utilizing a Philbrick-Nexus type 4358 module. A Moseley 7000A xy plotter then records the logarithm of the quotient of the lock-in output and the dc beam signal. The total beam current normalizes the metastable signal, compensating for source drifts and geometric losses as the ions traverse the drift tube. The x axis of the plotter, calibrated in meters of displacement, is driven by a voltage divider using a precision 40-turn potentiometer geared directly to the detector transport system. Exponential decay curves appear as straight lines on the plotter.

In the drift tube the He^+ beam is contained by an axial magnetic field of approximately 100 G. With careful beam alignment it is found that geometric losses are negligible over a 6-m interval. The vacuum chamber and its contents are of nonmagnetic stainless-steel construction. A base pressure of 2×10^{-8} Torr is attained by liquid-nitrogen–trapped mercury diffusion pumps at the ends of the drift tube, which is bakable at 120°C. Molecular-sieve foreline traps serve to prevent hydrocarbon contamination.

In a test to rule out the possibility that electrons from the source might be accelerated by the microwave field and included in the beam, a 25-V positive bias potential was applied to the detector plate, and the bombarding voltage was reduced below the 65-V metastable production threshold. The very small (10^{-13}-A) electron currents detected were observed to have the same 65-V production threshold as the metastable ions in the beam, and we conclude that they are due to secondary emission from the grids.

The axial velocity distribution for the ions was determined by means of a retarding potential applied to the inner grid. The spread in ion energies was found to be less than 0.7 eV full width

at half-maximum, corresponding to a 2.5% spread in axial velocities. Since the velocity distribution is nearly symmetric about the value $v = 2.86 \times 10^4$ m sec^{-1}, corrections for the spread are well under 1% and therefore negligible.

The loss of metastable current in flight is approximately 15% in a 6-m beam length. On an expanded scale of the plotter, the decay curve is a straight line with a small shot-noise contribution. The potentiometer circuit, logarithmic amplifier, and plotter introduce a combined error less than 0.3% in the observed slope. Slopes determined in this way are proportional to the decay rate Γ_{tot}:

$$\Gamma_{tot} = -v \frac{d}{dx}\left(\log_{10} \frac{I_{ac}}{I_{dc}}\right) \ln 10, \quad (3)$$

where x denotes the position of the detector.

Sources of possible systematic error include Stark quenching of metastable ions by stray electric or motional electric fields and also collisional de-excitation by residual gas molecules present in the drift tube. All of these effects would tend to increase the measured decay rate. There is no evidence for stray fields due to charged walls of the vacuum chamber, as the observed rate is independent of the total beam current. Changes in the axial magnetic field between 50 and 200 G likewise have no identifiable effect on the decay rate, and we therefore assume that we may neglect corrections for motional electric fields due to azimuthal velocity components associated with the helical ion motion. The collision quenching rate is expected to be proportional to the pressure of gas in the drift tube. Introduction of a known target gas permits a direct measurement of the de-excitation cross section. Slow ions created in charge-exchange processes are repelled by a small positive potential on the inner grid of the detector. For the de-excitation of $He^+(2S)$ by helium and nitrogen, we have measured the following values of the total cross section:

$$\sigma_{He} \simeq 10\pi a_0^2, \quad \sigma_{N_2} = 50\pi a_0^2. \quad (4)$$

The decay rate is plotted as a function of N_2 pressure in Fig. 2.

Before corrections for residual gas quenching, an average over 22 5-min scans yielded a total decay rate

$$\Gamma_{tot} = 508 \pm 95 \text{ sec}^{-1}. \quad (5)$$

With the ion source in operation a pressure of 4×10^{-8} Torr (N_2 ion gauge calibration) was measured at the ends of the drift tube. The decay-rate contribution due to quenching by helium is 3 sec^{-1}, determined from the 0.6×10^{-8} Torr reduction in ion-gauge reading when the gas flow to the source chamber is interrupted. If it is assumed that the remaining gas is nitrogen, its contribution is 14 sec^{-1}. The composition of the residual gas is not known, however, and during bakeout of the drift tube we have noted a vapor having a large quenching cross section ($\sigma = 870F \times \pi a_0^2$, where F is an ion-gauge correction for the unknown gas). Polar molecules such as H_2O are expected to have cross sections of this order.[13] A decay-rate correction for residual gas of this composition would further reduce the experimental value of the decay rate, and therefore it is appropriate to extend the uncertainty toward smaller values of Γ:

$$\Gamma = 491^{+95}_{-140} \text{ sec}^{-1}, \quad \tau = 2.04^{+0.81}_{-0.34} \text{ msec}. \quad (6)$$

Since $\Gamma_{theor} = 525$ sec^{-1}, a conservative assumption is that $\Gamma_a \leq 95$ sec^{-1}. Using Eq. (2), with the experimental value of δ for He^+,[14] we conclude $\lambda \leq 8 \times 10^{-5}$.

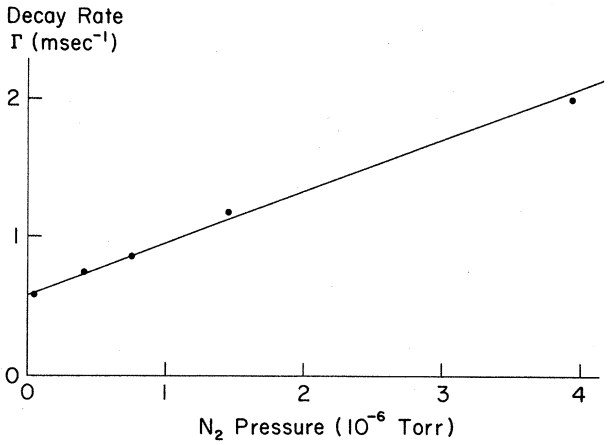

FIG. 2. Variation of decay rate with pressure for N_2 target gas.

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[1]S. Klarsfeld, Phys. Lett. 30A, 382 (1969).

[2]G. Feinberg, private communication.

[3]E. Commins, L. Gampel, M. Lipeles, R. Novick, and S. Schultz, Bull. Amer. Phys. Soc. 7, 258 (1962).

[4]M. Lipeles, R. Novick, and N. Tolk, Phys. Rev.

Lett. 15, 690 (1965).
[5]C. J. Arthur, N. Tolk, and R. Novick, Astrophys. J. Lett. 157, L181 (1969).
[6]R. Novick, in *Physics of One- and Two-Electron Atoms*, edited by F. Bopp and H. Kleinpoppen (North-Holland, Amsterdam, 1969), pp. 296-325.
[7]Ya. B. Zel'dovich, Zh. Eksp. Teor. Fiz. 33, 1531 (1957), and 36, 964 (1959) [Sov. Phys. JETP 6, 1184 (1958), and 9, 682 (1959)].
[8]B. Sakitt and G. Feinberg, Phys. Rev. 151, 1341 (1966).
[9]M. C. Weisskopf and E. Lipworth, in *Physics of One- and Two-Electron Atoms*, edited by F. Bopp and H. Kleinpoppen (North-Holland, Amsterdam, 1969), pp. 152-158.
[10]R. Marrus and R. Schmieder, Phys. Rev. A 5, 1160 (1972).
[11]S. Dworetsky, R. Novick, W. W. Smith, and N. Tolk, Rev. Sci. Instrum. 39, 1721 (1968).
[12]H. D. Hagstrum, Phys. Rev. 104, 309, 672 (1956).
[13]The similar case of H(2*S*) de-excitation is discussed by J. I. Gersten, J. Chem. Phys. 51, 637 (1969).
[14]E. Lipworth and R. Novick, Phys. Rev. 108, 1434 (1957).
[15]M. H. Prior, preceding Letter [Phys. Rev. Lett. 29, 611 (1972)].

Coincidence Measurement of Quasifree Scattering of 9-keV Electrons on *K* and *L* Shells of Carbon

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Momentum distributions of electrons bound in the *K* and *L* shells of carbon have been separately measured. Data obtained from the angular distribution of coincidences between the two electrons outcoming in a quasifree $(e,2e)$ process are compared with theoretical predictions.

The problem of measuring electron momentum distributions (EMD's) in atoms, molecules, and crystals is a long-standing one. The techniques used until now to obtain these distributions include Compton scattering of x rays,[1] quasifree electron scattering at large angles,[2] and positron annihilation.[3] In the published experiments only one of the three reaction products has been detected. In this way it is impossible to resolve EMD's due to electrons belonging to different bound states. In spite of this limitation, interesting information has been obtained, particularly from the study of the broadening of the Compton lines. Even when the initial state of the bound electron is defined, as for instance when the scattered x ray is taken in coincidence with a fluorescence photon,[4] the Compton profile does not give direct information on the EMD because it is determined by an integral of this function. A possible way to overcome these difficulties consists in using high-energy electrons and in measuring the angular correlation of the scattered and ejected electrons detected in coincidence. To simplify the interpretation of the results, the process has to be a "quasifree" scattering and the energies and momenta of the particles must be measured with great relative accuracy. In this way direct measurements of EMD's of well-defined initial states can be obtained. Of course the improvement of information goes together with an increase in experimental difficulties because of the smaller values of the cross sections involved and the much more stringent experimental requirements.

In the last few years theoretical papers have been published suggesting the use of electron coincidence techniques for measuring EMD's in atoms, molecules, and solids,[5] but experimental results are still lacking. Only Amaldi *et al.*[6] have demonstrated the feasibility of these $(e,2e)$ experiments using an apparatus whose resolving power is enough to separate $(e,2e)$ events produced by scattering on *K* and *L* shells of carbon. Preliminary measurements of the angular distributions on Formvar targets have also been presented.[7]

In the framework of the impulse approximation, justified by the high kinetic energies of the electrons and by the high momentum transfer in the