[6] Only true for rarefied gases. For a pressure of 0.1 Torr, $\tau_{sel}/\tau_{mfc} \sim O(10^{-2})$, at room temperature.

[7] M. Born and R. Oppenheimer, Ann. Phys. (Leipzig) 84, 747 (1927).

[8] R^* may be estimated from $MV^2/2 = 3kT/2 \gg \alpha/R^6$, $R \ll (\alpha/3kT)^{1/6}$, and $R^* = \xi(\alpha/3kT)^{1/6}$, where $\xi \gg 1$.

[9] The reason for taking the average before we take the square of the matrix element is given by Feynman on a probability-amplitude argument in R. P. Feynman, Rev. Mod. Phys. 20, 267 (1948).

[10] E. A. Power, *Introductory Quantum Electrodynamics* (American Elsevier, New York, 1965), Chap. VII.

Radiative Lifetime of the Metastable 2^1S_0 State of Helium*

R. S. Van Dyck, Jr., C. E. Johnson, and H. A. Shugart
Department of Physics and Lawrence Radiation Laboratory, University of California, Berkeley, California 94720

(Received 11 September 1970)

Two fixed, spatially separated detectors are used to measure the decay in flight of a cooled, thermal beam of pulsed metastable helium atoms. The preliminary value obtained for the radiative lifetime of the metastable 2^1S_0 state of helium is 20 ± 2 msec.

The 2^1S_0 state of helium is metastable, decaying predominantly by two photons[1]; single-photon decay is forbidden by the rigorous selection rule $J=0 \not\to J=0$. In this Letter we describe our effort to determine the lifetime of the 2^1S_0 state of helium. An earlier version of this experiment[2] was limited by pressure-dependent scattering and yielded a lower limit of $\tau = 9$ msec for the 2^1S_0 lifetime. Pearl,[3] in an experiment using a detector traveling over a 1-m length, has recently reported a result $\tau = 38 \pm 8$ msec for the lifetime. Drake, Victor, and Dalgarno[4] have calculated, however, the theoretical value $\tau = 19.5$ msec.

Our time-of-flight experimental arrangement is illustrated in Fig. 1. Helium atoms effusing from a source slit pass vertically through the open end of a sheath electrode gun[5] and are metastabilized by an antiparallel, magnetically focused electron beam of about 40 eV. The atomic beam then contains primarily ground-state helium atoms and metastable atoms in both the 2^3S_1 and the 2^1S_0 excited states. The ground-state and metastable-state atoms are separated by their different effects on the copper targets; the metastable atoms have sufficient energy to eject an electron from a target while the ground-state atoms do not. The electrons are collected and counted by an EMI electron mulitplier. Two fixed detectors located 1.9 and 6.7 m from the electron gun are used, the first having a transmission of about 50%. The beam is highly col-

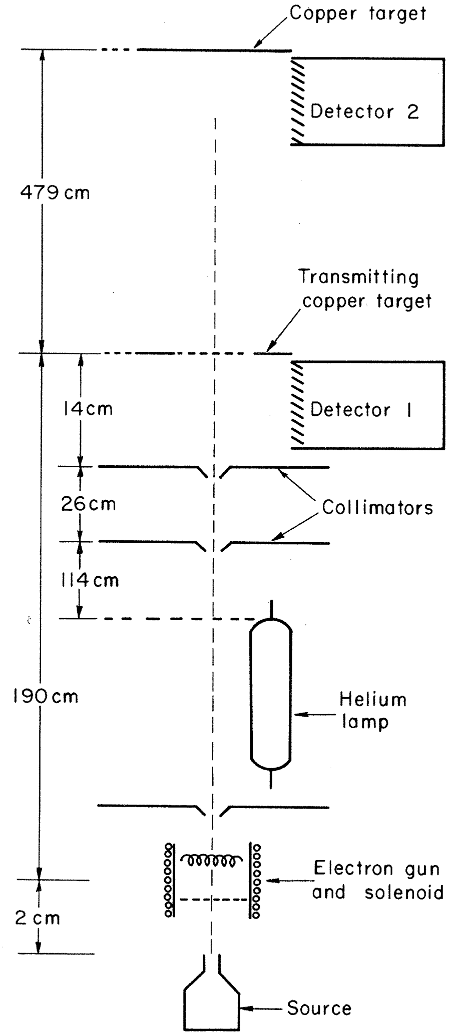

FIG. 1. Schematic diagram of the time-of-flight apparatus. Helium atoms effusing from the cooled source are metastabilized by an antiparallel electron beam, collimated, and then detected at detectors 1 and 2; the discharge lamp allows the separation of the 2^1S_0 and the 2^3S_1 metastable states. A determination of the number of 2^1S_0 atoms decaying between the two detectors gives the radiative lifetime.

limated after leaving the electron gun and provision is made for cooling the source with either liquid nitrogen or liquid helium. Since a low base pressure in the drift region between the two detectors is essential to minimize scattering effects, the apparatus is of all-metal bakable construction; during operation the base pressure is at least 1×10^{-8} Torr. Sufficient buffer chambers are provided to insure that there is no detectable rise in the drift-region pressure while a helium beam is running.

The time-of-flight spectrum for the metastable 2^1S_0 state can be separated from that of the 2^3S_1 state by using an rf-discharge helium lamp. The 2^1S_0 state is quenched by absorption of a 20 580-Å photon, raising the atom to the 2^1P_1 state, which then decays preferentially to the $^1S_0$ ground state.[6] The triplets are essentially unaffected by the lamp since the metastable 2^3S_1 state is the ground state of the triplet system. The number of atoms reaching the detectors for the full beam containing both 2^3S_1 and 2^1S_0 atoms is $N(^3S_1)+N(^1S_0)$, while the number in the quenched beam is $N(^3S_1)+(1-f)N(^1S_0)$; f represents the fraction of 2^1S_0 atoms that are quenched and is typically about 98%. The time-of-flight spectrum for the 2^1S_0 atoms is therefore obtained from the difference between the full beam and the quenched beam and is $n=fN(^1S_0)$. The lamp is positioned close to the electron gun so that the uv-quench photons have a small probability of reaching the detectors; therefore, they do not interfere with the time-of-flight spectrum of the pulsed metastable beam.

The data collection and timing aspects of this experiment are controlled by a PDP-8 computer (see Fig. 2). Channel-advance pulses are generated every 100 μsec and determine the widths of both the electron-gun pulse and the time-of-flight collection channels. The electron gun is pulsed on during the first channel and is then turned off while the time-of-flight spectrum is collected in the next 199 channels. The computer also turns the discharge lamp on and off during alternate collection cycles, allowing the collection of the spectrum for both the full and the quenched beams. The 2^1S_0 spectrum is obtained during analysis of the collected data to determine the lifetime of this metastable state. An example of a 2^1S_0 time-of-flight spectrum is illustrated in Fig. 3(a).

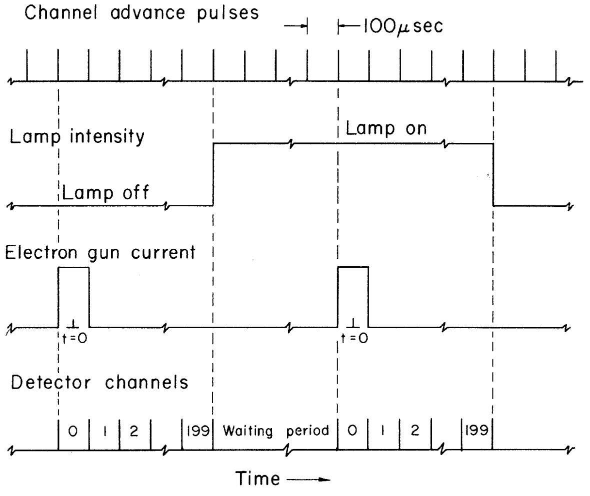

FIG. 2. Timing arrangement used to obtain the time-of-flight spectrum of the metastable helium atoms. Timing and data collection are controlled by a PDP-8 computer.

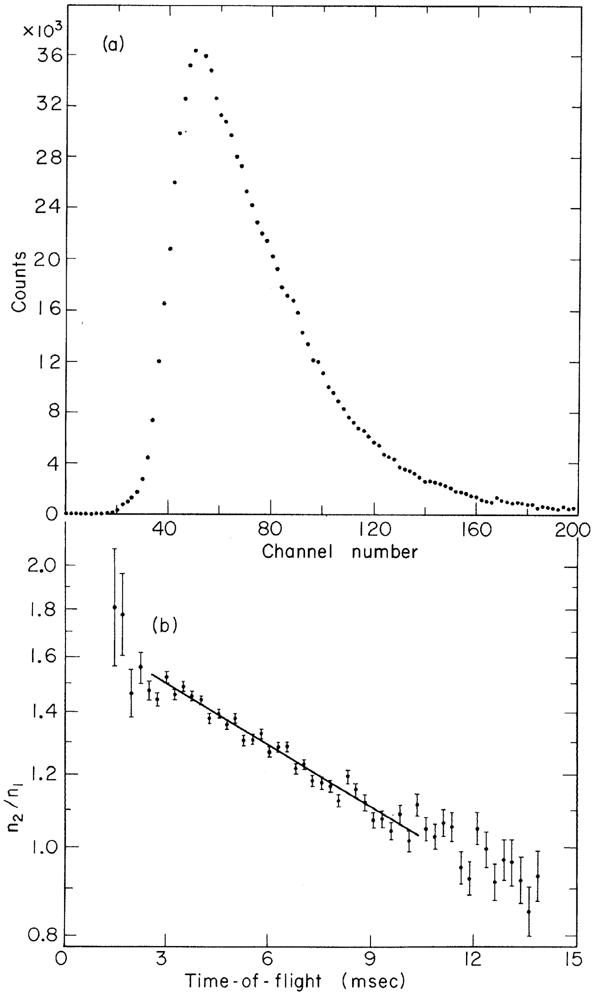

FIG. 3. (a) Metastable 2^1S_0 time-of-flight spectrum obtained at detector 2. (b) Corresponding logarithmic decay plot of $R(t)=n_2/n_1$ versus the time of flight t. The slope of the least-squares-fitted straight line is $-1/\tau$, with $\tau=19.9\pm0.8$ msec; only points with a number of counts greater than 1% of the peak are included in the fit.

If the velocity distribution of 2^1S_0 atoms arriving at the first detector is $n_0(v)$, then the number of atoms detected is

$$n_1(v) = \int_{\text{surface}} \epsilon_1 n_0(v) dS_1; \tag{1}$$

ϵ_1 is an experimental detection efficiency factor and is a function of the position on the copper target where a 2^1S_0 atom strikes. Likewise, allowing for the possibility of radiative decay between detectors, the number of 2^1S_0 atoms detected at the second detector is

$$n_2(v) = \int_{\text{surface}} \epsilon_2 n_0(v) e^{-t/\tau} dS_2, \tag{2}$$

where $t = d/v$ is the time of flight between the two detectors a distance d apart. The assumption used in Eq. (2), and in fact basic to the time-of-flight technique for measuring lifetimes, is that only radiative decay occurs during the atom's flight between detectors. Thus, low pressures are absolutely essential both in the beam and in the drift region to minimize systematic effects from scattering. We do not observe, within our present error, any significant change in the measured lifetime whenever either the drift-region pressure varies from 10^{-7} to 10^{-8} Torr or the helium-beam flow rate varies by a factor of 10. An additional indication of the lack of a systematic pressure effect is that an analysis of the quenched-beam time-of-flight spectrum, consisting mostly of 2^3S_1 atoms, yields a lower limit of about 700 msec for the 2^3S_1 lifetime.

A result independent of the initial velocity distribution $n_0(v)$ is obtained if every position on the detector sees the same distribution. The ratio of Eqs. (1) and (2) is then simply

$$R(t) \equiv n_2(v)/n_1(v) = C e^{-t/\tau}, \tag{3}$$

where both detector efficiencies are combined into a single constant C. Illustrated in Fig. 3(b) is a logarithmic plot of $R(t)$ vs t for a 2^1S_0 time-of-flight spectrum taken during a data collection time of about 2 h. The lifetime of the metastable 2^1S_0 state is obtained from the slope of the least-squares-fitted straight line; only points with a number of counts greater than 1% of the peak are included in the fit. Equation (3) is not valid unless every position on the detector has the same initial velocity distribution $n_0(v)$; however, this may not be true in practice. We have observed large changes of about 50% in the measured 2^1S_0 lifetime resulting not only from varying the collection potential applied to the detector, but also from moving the source position perpendicular to the beam direction. The elimination of this effect to within our present error requires a metastabilizing electron beam antiparallel instead of perpendicular to the helium beam. This provides an initial velocity distribution less dependent on the observation angle, and insures that every position on the detector sees essentially the same distribution.

The radiative lifetime for two-photon decay of the metastable 2^1S_0 state of helium which we have measured is $\tau = 20 \pm 2$ msec. This result is an average over 45 runs in which the possible experimental variables were systematically changed; within our present error, there is no change in the 2^1S_0 lifetime resulting from a variation of such parameters as electron-gun voltage, source position, source temperature, lamp intensity, beam flow rate, detector potentials, and drift region pressure. Clearly, our result for the 2^1S_0 lifetime agrees well with the theoretical value $\tau = 19.5$ msec calculated by Drake, Victor, and Dalgarno,[4] but not with the experimental one of $\tau = 38 \pm 8$ msec reported by Pearl.[3] Our work is still proceeding to understand completely the extent of any systematic errors and to eliminate them if possible. The results of this work as well as additional details of the experiment will be reported later.

---

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

[1] M. Mayer, Ann. Phys. (Leipzig) 9, 273 (1931); G. Breit and E. Teller, Astrophys. J. 91, 215 (1940).

[2] M. Steinberg and H. A. Shugart, Bull. Amer. Phys. Soc. 14, 32 (1969).

[3] A. S. Pearl, Phys. Rev. Lett. 24, 703 (1970).

[4] G. W. F. Drake, G. A. Victor, and A. Dalgarno, Phys. Rev. 180, 25 (1969). For previous theoretical results see A. Dalgarno, Mon. Notic. Roy. Astron. Soc. 131, 311 (1966); A. Dalgarno and G. A. Victor, Proc. Phys. Soc., London 87, 371 (1966); G. A. Victor, Proc. Phys. Soc., London 91, 825 (1967).

[5] W. E. Lamb and R. C. Retherford, Phys. Rev. 81, 222 (1951).

[6] E. S. Fry and W. L. Williams, Rev. Sci. Instrum. 40, 1141 (1969).