of the data on Fig. 7, the excess carrier lifetime can be determined. Figure 8 is a plot of the excess carrier lifetime as a function of $1000/T$ for the same sample as measured in Fig. 5. A discussion of the data presented in Figs. 5 and 8 is given elsewhere.[8] The above analysis is performed in a minimum of time by the use of a semiautomatic film reader and a computer program.

ACKNOWLEDGMENT

The authors thank Dr. V. A. J. van Lint for initiating this work and providing invaluable assistance.

---

[8] R. Leadon and J. A. Naber, J. Appl. Phys. 40, 2630 (1969).

THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 40, NUMBER 9 SEPTEMBER 1969

Production of a 2^3S Helium Beam*

E. S. Fry† and W. L. Williams

Harrison M. Randall Laboratory of Physics, The University of Michigan, Ann Arbor, Michigan 48104

(Received 24 March 1969; and in final form, 23 April 1969)

Beams of metastable helium produced by electron bombardment generally contain atoms in both the 2^1S and 2^3S states. It is important in many experiments to distinguish between these states, or at least to know the population ratio. A beam of 2^3S and ground state helium atoms has been produced by electron bombardment and subsequent resonant quenching of 2^1S atoms with 2^1S–2^1P 2 μ radiation. This radiation mixes the 2^1S and 2^1P states, the latter decaying primarily to the 1^1S state by emission of 584 Å radiation. The quenching has been studied as a function of beam atom velocity. The results indicate that beams of metastable helium containing less than 1% 2^1S atoms can be produced.

INTRODUCTION

BEAMS of metastable helium produced by electron bombardment generally contain atoms in both the singlet (2^1S_0) and triplet (2^3S_1) states. It is important in many experiments to distinguish between these metastable states, or at least to know their relative populations. In previous experiments the populations of these states were determined in one of two ways. One method utilizes a Stern–Gerlach magnet to separate atoms in the $m=+1$ and $m=-1$ substates of the 2^3S state from the beam. An assumption of equal populations among the three substates $m=0, \pm 1$ then makes it possible to determine the fraction of the beam in the 2^3S state.[1] In the second method a dc electric field is used to couple the 2^1S state to excited states which have short lifetimes against radiative decay to the ground (1^1S) state (Stark quenching). This permits a direct determination of the fraction of singlet metastable atoms in the beam. However, due to the large separation (0.6 eV) from the nearest short lived state (2^1P), only 90% of the singlets could be quenched with fields of 2×10^5 V/cm.[2]

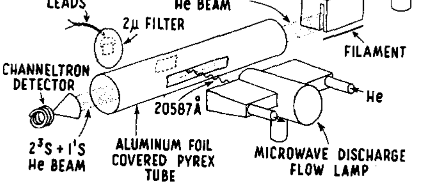

FIG. 1. Schematic diagram of the apparatus.

We report here a simple method for the production of atomic beams containing helium atoms in only the 2^3S_1 and 1^1S_0 states. We accomplish this by resonant Stark quenching of atoms in the 2^1S state with 2^1S–2^1P 2 μ radiation. This radiation mixes the 2^1S state with the 2^1P state, which decays mainly to the ground 1^1S state with emission of 584 Å radiation.[3]

I. EXPERIMENTAL

The experimental arrangement is shown in Fig. 1. A rectangular 0.050×0.65 cm slit in a helium source tube at 300 K together with appropriate collimation provides a ribbon shaped beam of ground state helium atoms. This beam is cross fired by a pulsed electron beam produced with a simple diode structure electron gun. The electron energy resolution is poor (~4 eV) due to the voltage drop across the filament. Emerging from the electron gun is a beam containing helium in the 1^1S ground state and in the 2^1S and 2^3S metastable states. Any other states are so short lived as to have decayed at any appreciable distance from the electron gun. Along with the atomic

---

* Supported in part by U. S. Atomic Energy Commission and University of Michigan Office of Research Administration.

† Present address: Department of Physics, Texas A & M University, College Station, Texas 77843.

[1] E. E. Muschlitz, Jr., Science 159, 599 (1968).

[2] H. Holt and R. Krotkov, Phys. Rev. 144, 82 (1966).

[3] W. L. Williams and E. S. Fry, Phys. Rev. Lett. 20, 1335 (1968); E. S. Fry and W. L. Williams, Bull. Amer. Phys. Soc. 13, 1397 (1968).

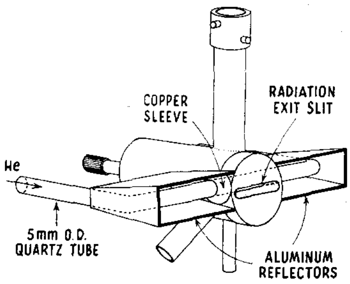

FIG. 2. Detail of the quenching lamp.

beam there is also a considerable amount of vacuum uv radiation produced in the electron bombardment region. The atomic beam passes along a 19 mm diam Pyrex tube approximately 60 cm in length to a Channeltron electron multiplier.[4] This device detects both the metastable component of the beam and the vacuum uv radiation produced in the electron gun, but does not detect the ground state helium atoms.[5]

Resonant 2^1S–2^1P 2 μ radiation is obtained from a microwave discharge helium lamp. Figure 2 shows a detail of the complete lamp assembly. The lamp is a 5 mm diam quartz tube through which helium flows at a pressure of ≈ 1 Torr. The quartz tube is placed in a slightly modified version of the microwave cavity No. 5 described by Fehsenfeld, Evenson, and Broida.[6] This cavity is driven with approximately 80 W of power at 2450 MHz by a Raytheon Microtherm diathermy machine. The resulting discharge extends well into the tubing outside the cavity giving a bright light source approximately 10 cm long. The two modifications to cavity No. 5 are (1) a 5 mm×2.3 cm slot in the cavity bottom through which light from the center of the discharge exits and (2) a copper sleeve that fits snugly into the bottom of the cavity and which clamps the 5 mm quartz tube against the back of the 13 mm slots in the cavity walls.

This lamp is placed adjacent to the Pyrex beam tube and the intensity of the 2 μ radiation is varied by insertion of appropriate Kodak Wratten filters between the lamp and the Pyrex beam tube. The 2 μ intensity is monitored with a Kodak Ektron detector placed on the side of the beam tube opposite the lamp. The effective 2 μ intensity incident on the beam has been increased by wrapping the beam tube with aluminum foil, leaving a 7 cm long by 1 cm high slot to admit the radiation and another smaller slot through which the intensity can be monitored. The aluminum foil also eliminated microwave pickup by the Channeltron. The intensity incident on the beam was further increased by means of aluminum reflectors around the sections of the quartz tube extending outside the microwave cavity.

Positive pulses of 75 V amplitude and 20 μsec width were applied to the anode of the electron gun. The repetition rate was 1000 Hz. Metastables and radiation are produced in the electron gun only during the time the pulse is applied. By observing the time of flight (TOF)[7] to the detector it is possible to distinguish between the metastables and the radiation since the velocity of the latter is 3×10^{10} cm/sec and therefore it arrives at the detector within a few nanoseconds. The metastables have thermal velocities ($\sim10^5$ cm/sec) and arrive at the detector several hundred microseconds after the electron gun has been pulsed. By utilizing TOF it is also possible to observe quenching as a function of metastable velocity. In particular, a 20 μsec wide gate can be set to select electronically any portion of the metastable time of flight distribution. Hence it is possible to study selectively metastables whose time of flight (and thus also velocity) lies within the limits set by the 20 μsec gate and by the 20 μsec electron gun pulse.

II. THEORY

The radiation induced decay rate Γ of the 2^1S metastable state is[8]

$$\Gamma=(2\alpha f\lambda\tau_P/mc)I, \tag{1}$$

where $\tau_P=5.8\times10^{-10}$ sec is the lifetime of the 2^1P state,[3] α is the fine structure constant, λ and I are, respectively, the wavelength and energy flux density of the incident resonant radiation, and f is the absorption oscillator strength for the 2^1S–2^1P transition. Using the theoretical value of $f=0.376$[9] one finds

$$\Gamma=2.33\times10^5 I\ \text{sec}^{-1}, \tag{2}$$

where I is in milliwatts per square centimeter. The fraction of 2^1S atoms with velocity v which is quenched in

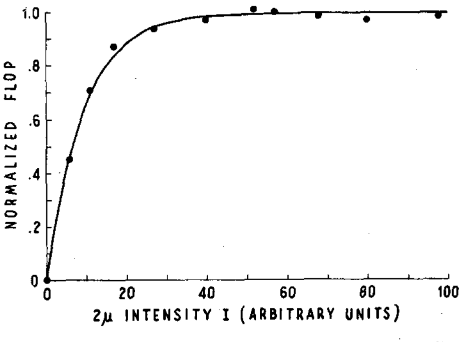

FIG. 3. Quench data for metastables with an intermediate time of flight. ●—experimental, ———least squares fit; pulse width 20 μsec, gate width 20 μsec; TOF 500 μsec.

---

[4] We are indebted to C. W. Hendee of Bendix Corp. for supplying the Channeltron multipliers used in this work.

[5] D. P. Donnelly, J. C. Pearl, R. A. Heppner, and J. C. Zorn, Rev. Sci. Instrum. **40**, 1242 (1969).

[6] F. C. Fehsenfeld, K. M. Evenson, and H. P. Broida, NBS Rep. 8701 (1964).

[7] J. B. French and J. W. Locke, in *Rarefied Gas Dynamics*, C. L. Brundin, Ed. (Academic Press Inc., New York, 1967), p. 1461.

[8] W. E. Lamb, Jr., and R. C. Retherford, Phys. Rev. **79**, 549 (1950).

[9] B. Schiff and C. L. Pekeris, Phys. Rev. **134**, A638 (1964).

a transition region of length l is given by[8]

$$F=1-e^{-\Gamma l/v}, \tag{3}$$

where F is called the normalized flop. In the present experiment for 63% quench with $v\approx 2\times 10^5$ cm/sec and $l=7$ cm, the required intensity of resonant 2 μ radiation is $I\approx 0.1$ mW/cm^2. The results to be discussed below indicate that this intensity is easily obtained.

III. RESULTS

Experimentally the flop is obtained by taking the difference between the helium metastable count rates with an opaque filter and with a partially transmitting filter between the quench lamp and the beam tube. By selecting metastables with a small range of times of flight with the 20 μsec gate and measuring the flop over a range of intensities from zero to maximum, one obtains the complete flop curve for the corresponding metastable velocity. These data are then least squares fitted to an equation of the form

$$F=A(1-e^{-BI}). \tag{4}$$

The data are then normalized by dividing by A. Aside from the amplitude A, Eq. (4) is identical to Eq. (3), the exponent $\Gamma l/v$ having been rewritten BI. B is proportional to time of flight and is therefore inversely proportional to velocity.

Figure 3 shows an example of a flop curve together with the least squares fit. The intensity axis is in arbitrary units. These data were for a time of flight of 500 μsec or a metastable velocity of $\approx 1.2\times 10^5$ cm/sec. Figure 4 summarizes the velocity dependence of the quench data. This is a plot of the fitted parameter B as a function of time of flight. B is in arbitrary units. As expected, the data points are best fit by a straight line, demonstrating the linear relationship between B and time of flight.

Figure 5 shows a second example of the quench data. Included in these flop data are all metastables which arrive at the detector at times between 100 and 900 μsec after the electron gun is pulsed. Essentially all the metastables produced have times of flight falling in this range. These data were fitted to Eq. (4) and then normalized. However, it should be noted that, for this case, B is not linearly related to time of flight but is a function of the complete range of times of flight. As shown in the figure, 99% quenching of all the 2^1S atoms in the beam is obtained at less than half the maximum intensity.

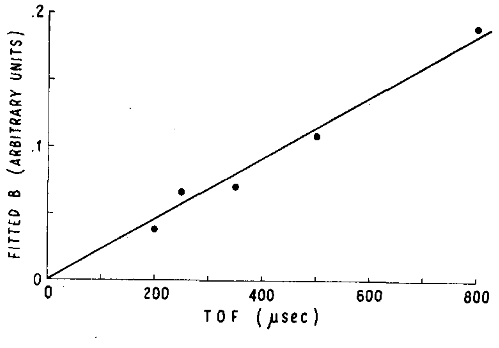

FIG. 4. Dependence of the fitted parameter B on time of flight.

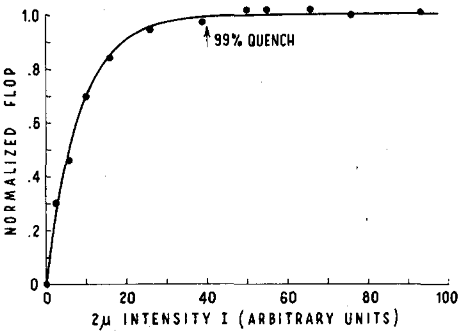

FIG. 5. Quench data for the entire metastable beam. Quenching of 99% is obtained at less than one-half the maximum available 2 μ intensity. ●—experimental, ———least squares fit; pulse width 20 μsec, gate width 800 μsec.

The fraction of the metastable beam in the 2^1S state appears to vary considerably with electron gun characteristics and atom velocity. However, accurate quantitative data are not available for two reasons. First, an experiment to determine the relative detection efficiencies of the Channeltron for singlet and triplet metastables has not yet been performed. Second, the 584 Å radiation emitted during the quenching process can be detected by the Channeltron. This could lead to erroneously large counting rates when the quench light is applied to the beam. Neither of these effects, however, will alter the shape of the quenching curves given by Eq. (4). As a matter of general interest, the absolute magnitudes of the counting rates for the data presented in Fig. 3 are 1.4×10^4 metastables/sec with an opaque filter between the beam and the lamp, and 9.6×10^3 metastables/sec with maximum 2 μ intensity. This leads to an uncorrected value of $\sim$32% for the 2^1S population in the metastable beam.

As mentioned earlier, 584 Å radiation is emitted during the quenching process. A second Channeltron was used to monitor that portion of the radiation which is emitted in a direction perpendicular to both the beam direction and the direction of the incident quenching light. As expected, it is found that the 584 Å intensity depends on 2 μ intensity in exactly the same way as flop given by Eq. (4). The fitted parameter B for these data has approximately the same value as that for the corresponding beam flop.