# Mean Lifetimes of the 2p and 3p Levels in He II

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(Received 17 April 1967)

The foil-excitation technique has been used to measure the mean lifetimes of the $2p$ and $3p$ levels in He II. The measured lifetimes agree with the theoretical values, the measured accuracy being $\pm 3\%$ for the $2p$ level and $\pm 10\%$ for the $3p$ level. The mean lives were determined from the decay of the two emission lines $1s$-$2p$ at 304 Å and $1s$-$3p$ at 256 Å as a function of distance from the intersection of the foil and beam. Cascading into the $2p$ and $3p$ levels was observed, and corrections for cascading were necessary to determine the lifetimes. The observed cascading was found to be in reasonable agreement with the theoretically predicted cascading from adjacent excited levels of He II.

## I. INTRODUCTION

RECENTLY, the lifetimes of several levels in atomic hydrogen have been determined experimentally. These measurements in general are in good agreement with the theoretical values of lifetimes which can be calculated exactly for any hydrogenlike ion. Bickel and Goodman[1] measured the mean lifetimes of the $2p$ and $3p$ levels of atomic hydrogen by using the foil-excitation technique. This technique consists of passing a beam of hydrogen ions of known velocity through a carbon foil from which a beam of atomic hydrogen emerges in various states of excitation. The lifetimes of the $2p$ and $3p$ levels were obtained from the spatial decay, along the ion beam, of the intensity of the two uv emission lines, Lyman $\alpha$ at 1216 Å and Lyman $\beta$ at 1026 Å, that originate from the $2p$ and $3p$ levels, respectively. The decay of Lyman $\alpha$ was corrected for cascading into the $2p$ level, and the measured mean life of the $2p$ state agreed with theory. Weak cascading into the $3p$ level was also observed in the decay of Lyman $\beta$, but corrections for cascading were not applied to the experimental data. A slight discrepancy of only 3% between the theoretical and measured mean life of the $3p$ level was attributed to the effects of this weak cascading on the decay of Lyman $\beta$. Goodman and Donahue[2] also used the foil-excitation technique to measure the mean lives of the states of the $n=3$ and 4 levels of hydrogen. They measured the spatial decay of the emission lines $H_\alpha$ and $H_\beta$ which were isolated with interference filters. Their measured values of lifetimes generally agreed with the theoretical values. Hughes *et al.*[3] also measured the mean lives of the fine-structure states of the $n=3$ level in hydrogen by using a method that was similar in principle to the foil-excitation technique. They observed the spatial decay of $H_\alpha$ that was produced by electron capture by fast $H^+$ ions colliding with neutral gases in a gas-filled collision chamber. The spatial decay of $H_\alpha$ measured after the partially neutralized beam left the chamber was decomposed graphically into three component decay times which agreed with the theoretical lifetimes of the $3s$, $3p$, and $3d$ levels. Recent measurements of the mean lifetimes of the $n=3$, 4, and 5 levels in hydrogen averaged over their fine-structure states have also been made by Ankudinov *et al.*[4]

Apparently the only measurement of lifetime for the hydrogen-like ion $He^+$ is that of Maxwell,[5] who measured the average mean lifetime of the states of the $n=6$ level. The He II emission line at 2733 Å, which originates from the $n=6$ level, was excited by an electron beam in helium at low pressure and the excited ions extracted by an electric field that was transverse to the direction of the electron beam. By observing the spatial distribution of intensity of the 2733 Å line in the direction of the electric field, Maxwell obtained an average mean lifetime for the $n=6$ level in good agreement with its theoretical value.

In the present experiment, the mean lifetimes of the $2p$ and $3p$ levels in He II were obtained by using the foil-excitation technique and measuring the spatial decay of the two transitions $1s$-$2p$ at 304 Å and $1s$-$3p$ at 256 Å. Cascading into the $2p$ and $3p$ levels was found to be important, and corrections for cascading were applied to obtain the lifetimes. Because the theoretical lifetimes in He II can be calculated precisely, experimental measurements in this atomic system provide an opportunity to examine in detail the accuracy that can be achieved in lifetime measurements with the foil-excitation technique when cascading is important. The analysis of cascading into the $2p$ and $3p$ levels in He II is particularly simple because the cascading transitions originate only from states having lifetimes that are appreciably longer than the lifetimes of the $2p$ and $3p$ levels. The cascading therefore is easily identified in the spatial decay of the He II emission lines 304 Å and 256 Å.

## II. EXPERIMENTAL METHOD

The experimental system has been described previously in detail.[6] A 1-MeV $He^+$ beam ($v=6.89\times10^8$

[1] W. S. Bickel and A. S. Goodman, Phys. Rev. **148**, 1 (1966).
[2] A. S. Goodman and D. J. Donahue, Phys. Rev. **141**, 1 (1966).
[3] R. H. Hughes, H. R. Dawson, and B. M. Doughty, J. Opt. Soc. Am. **56**, 830 (1966).
[4] V. A. Ankudinov, S. V. Bobashev, and E. D. Andreev, Zh. Eksperim. i Teor. Fiz. **48**, 40 (1965) [English transl.: Soviet Phys.—JETP **21**, 26 (1965)].
[5] L. R. Maxwell, Phys. Rev. **38**, 1664 (1931).
[6] L. Heroux, Phys. Rev. **153**, 156 (1967).

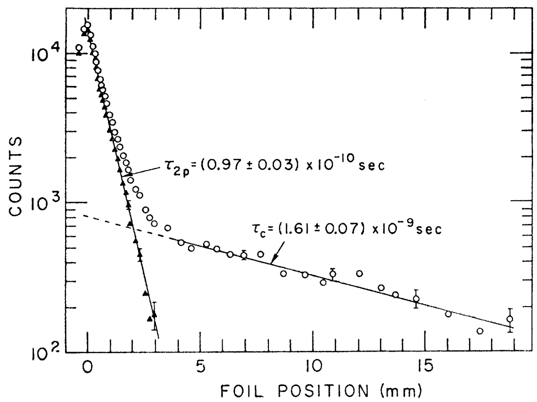


FIG. 1. Counts versus foil position for the line He II 304 Å. The data were obtained with a foil thickness of 500 Å, a beam energy of 1 MeV, and a counting interval of 100 sec. ○, data corrected for background; ▲, data corrected for both noise and cascading.

cm/sec) was passed through a carbon foil having a thickness of 10 $\mu$g/cm². The direction of the ion beam was normal to the plane of the foil. The emission spectrum of He II was observed with a grazing incidence monochromator that viewed the beam at 90° to the beam direction at a distance $l$ downstream from the intersection of the foil and beam. The length of the ion beam $\Delta l$ subtended by the aperture of the monochromator was about 1 mm. The foil was moved in small steps along the axis of the beam which enabled the intensity of the emission lines of He II to be measured as a function of distance.

The monochromator covered the wavelength region between 60 Å and 325 Å with an instrumental linewidth of about 0.5 Å. The beam current transmitted through the foil and collected on an insulated flange was approximately 2 $\mu$A. Photon-counting techniques were used to measure the spatial decay of the emission lines; because of the low photon fluxes, counting intervals of 100-sec duration were used for each foil position. The background counting rate of the system with the accelerator operating was about 4 counts/sec. Although small, this background rate limited the experimental data to measurements of the two He II emission lines 304 Å and 256 Å, the first two members of the He II Lyman series.

## III. RESULTS

Figure 1 presents the experimental data for the $1s$-$2p$ transition in He II at 304 Å. The data plotted as open circles have been corrected for a constant background only. Because the corrected signal decreases progressively with increasing distance from the foil, the standard deviation of these data increases with increasing distance from the foil. A few values of the standard deviation for different foil positions are indicated in the figure. As can be seen from Fig. 1, the decay of the line He II 304 Å is not a simple exponential, but is comprised of an initial rapid decay followed by a slower decay for foil positions above about 4 mm. The slow limiting decay is due to cascading transitions from upper excited states into the $2p$ level. The effect of the cascading process is to repopulate the $2p$ level partially, along the entire length of the ion beam, at a rate determined by the mean lives of the upper states from which the cascades originate. In He II, the lifetimes of these upper cascading states are appreciably longer than the lifetime of the $2p$ level. The initial rapid decay in count rate between $l=0$ and 4 mm must therefore be corrected for cascading to determine the mean life of the $2p$ level.

When a single cascade transition alone is important, the cascading decay will be characterized by a unique lifetime, and the cascade contribution at small foil positions can then be accurately established by projecting the slope of the cascade decay toward $l=0$. However, for He II, one would expect the observed cascading into the $2p$ level to be a superposition of cascade transitions from several upper levels, each having a different lifetime. The rather large standard deviations in the experimental data for the cascade decay in Fig. 1 do not permit separation of the individual cascade transitions. The cascade decay was therefore fitted to a straight line which was then extended toward the origin to estimate the cascade contribution at foil positions between 0 and 4 mm. The mean life assigned to this approximation for the cascading decay, $\tau_c = (1.61 \pm 0.07) \times 10^{-9}$ sec, was obtained from a least-squares fit of a straight line to the experimental data. The indicated error is the probable error of the least-squares fit. Although the value $\tau_c$ can be only a qualitative representation of the temporal characteristics of the cascading processes into the $2p$ level, this experimental value is in good agreement with the value expected for a straight-line approximation of the cascading from the two upper levels $3d$ and $4d$ into the $2p$ level (see Sec. IV).

When the contribution from cascading given by the broken line in Fig. 1 is subtracted from the initial rapid decay of He II 304 Å, the solid triangles in Fig. 1 are obtained. A least-squares fit of a straight line to these corrected data gives the mean life of the $2p$ level $\tau_{2p} = (0.97 \pm 0.03) \times 10^{-10}$ sec. The approximation of the complex cascading processes into the $2p$ level by a straight line introduces some error in the magnitude of the cascade contribution for small $l$ values which, in turn, introduces an error in the determination of $\tau_{2p}$. This error in $\tau_{2p}$ is discussed further in Sec. IV and is estimated to be less than $\pm 1\%$. The error indicated for $\tau_{2p}$ in Fig. 1 includes the probable error of the least-squares fit, an estimated error introduced by the cascade correction, and the error in the determination of the velocity of the ion beam that is estimated to be about $\pm 1\%$. Errors due to short-term fluctuations of the ion-beam current appeared to be small,[6] and this source of error is included in the probable error of the least-squares fit. This experimental value for $\tau_{2p}$ is in good agreement with its theoretical value listed in Table I.

A similar analysis of the data was applied to the emission line He II 256 Å to determine the mean life of the $3p$ level of He II. Figure 2 presents measurements for the $1s$-$3p$ transition in He II at 256 Å. To emphasize the presence of cascading, the uncorrected data, signal plus background noise, are plotted as solid circles. The noise level is also indicated in the figure. The scattering of the experimental data is large because the emission line is weak. The slow decay for foil positions greater than 7 mm is assumed to originate from weak cascading. A least-squares fit of a single straight line to this slow decay gives a cascading lifetime $\tau_c = (9.1 \pm 4.3) \times 10^{-9}$ sec that agrees qualitatively with that expected for a straight-line approximation for the complex cascading from the upper levels $4d$, $5d$, and $4s$ into the $3p$ level of He II (Sec. IV).

Correcting the experimental decay of He II 256 Å for both background and cascading gives the mean life $\tau_{3p} = (0.31 \pm 0.03) \times 10^{-9}$ sec. This measured value for $\tau_{3p}$ is also in good agreement with theory (see Table I). The error indicated for $\tau_{3p}$ was estimated graphically by applying to the experimental data a range of cascade corrections corresponding to the large probable error in $\tau_c$. Other errors of the type discussed previously for the decay of He II 304 Å were negligible in comparison to the error introduced into $\tau_{3p}$ by the indicated error in $\tau_c$ of about $\pm 50\%$.

## IV. DISCUSSION

The theoretical values of the mean lifetimes of several lower levels in He II are listed in Table I. The table is restricted to the $2p$ and $3p$ levels, measured here, and those levels of He II which are expected to be of importance in the present experiment because of cascading into either the $2p$ or the $3p$ levels.[7] The values were obtained by using the theoretical values of the transition probabilities for hydrogen, $A_H$, listed by Wiese

TABLE I. Theoretical and experimental mean lifetimes of He II.

| Level | Theoretical[a] mean life ($10^{-9}$ sec) | Experimental mean life ($10^{-9}$ sec) |
|---|---|---|
| $2p$ | 0.0998 | $0.097 \pm 0.003$ |
| $3p$ | 0.330 | $0.31 \pm 0.03$ |
| $3d$ | 0.967 | |
| $4d$ | 2.26 | |
| $5d$ | 4.35 | |
| $3s$ | 9.90 | |
| $4s$ | 14.2 | |

[a] Calculated by using values of transition probabilities for hydrogen listed by Wiese *et al.* (Ref. 8).

[7] H. A. Bethe and E. E. Salpeter, *Quantum Mechanics of One- and Two-Electron Atoms* (Springer-Verlag, Berlin, 1957), p. 267.

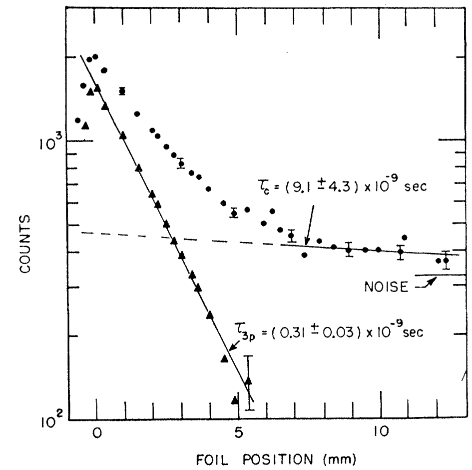


FIG. 2. Counts versus foil position for the line He II 256 Å. The counting interval for each point was 100 sec, the foil thickness was 500 Å, and the beam energy was 1 MeV. ●, uncorrected data; ▲, data corrected for both background and cascading.

*et al.*[8] and the additional relationship $A_{\text{He II}} = 16 A_H$ for the equivalent transitions in He II and H.

The magnitude and the spatial decay of the cascading processes into the $2p$ and $3p$ levels depend upon the initial population ($l=0$) of the upper levels from which the cascades originate, upon the fraction of transitions out of these upper levels that terminate on the $2p$ and $3p$ levels (the branching fraction), and upon the lifetimes $\tau_{c'}$, of the cascading states.[1] The contribution of the particular cascade transition to the measured counting rate also depends rather strongly on the incremental length $\Delta l$ of the ion beam that is viewed by the aperture of the monochromator.[6] When $\Delta l$ is small in comparison to $v\tau_{c'}$, only a small fraction, $\Delta l / v\tau_{c'}$, of the total cascade transitions that are distributed along the ion beam will occur within the aperture of the monochromator. For this reason, cascading transitions from upper levels having lifetimes that are appreciably longer than the lifetimes of the $2p$ and $3p$ states will not strongly influence the decay of the He II emission lines 304 Å and 256 Å. Since the mean lives of the levels in He II, for a particular value of angular momentum, in general increase progressively with increasing principal quantum number, only a few of the lower levels will contribute to cascading. These lower levels are listed in Table I. As an example, for the values of $\Delta l$ and $v$ used here, $\Delta l / v\tau_{c'}$ is only 0.015 for the cascade transition $2p$-$3s$ and this fraction decreases rapidly for cascades into the $2p$ level from higher $s$ levels. Similarly, cascade transitions of the type $2p$-$nd$, $n > 4$, would be expected to have only a minor influence on the experimental spatial decay of the He II 304 Å emission line.

[8] W. L. Wiese, M. W. Smith, and B. M. Glennon, *Atomic Transition Probabilities* (U.S. Government Printing Office, Washington, D.C., 1966), Vol. I.

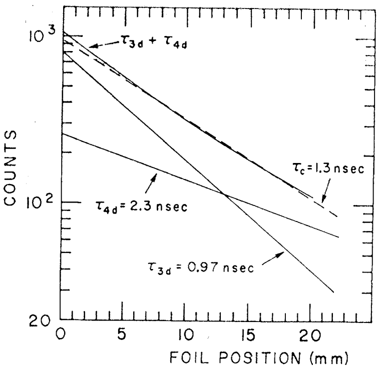


FIG. 3. Calculated cascade decay for the emission line He II 304 Å due to the predominant cascade transitions from the $3d$ and $4d$ levels into the $2p$ level. The total cascade contribution is represented by the complex curve $\tau_{3d}+\tau_{4d}$, while the broken line is the straight-line approximation of this complex decay.

The accuracy of the data in Fig. 1 is good enough to permit a comparison between the measured and the theoretically predicted cascading into the $2p$ level. The two cascade transitions $2p$-$3d$ and $2p$-$4d$ would be expected to influence the decay of He II 304 Å because the mean lives of the $3d$ and $4d$ states are reasonably close to the mean life of the $2p$ level, and the branching fractions for the transitions are large. Figure 3 presents the calculated effect of the cascade transitions $2p$-$3d$ and $2p$-$4d$ on the decay of the 304 Å line when measured with the present experimental parameters. To construct Fig. 3, it was assumed that the initial populations of the $3d$ and $4d$ levels were identical and that the branching fractions for the transitions $2p$-$3d$ and $2p$-$4d$ were the calculated values 1.0 and 0.74, respectively. The assumption of identical initial populations for the $3d$ and $4d$ levels is equivalent to assuming that the small difference in the large excitation energies of the two levels does not influence their relative populations and that the two levels are populated in accordance with their statistical weights only. Because of the additional factors $\Delta l/v\tau_{c'}$ for the two cascading transitions, the ratio of the intercepts of the counts contributed by the cascades at $l=0$ is $I_{3d}/I_{4d}=(1/0.74)\times(\tau_{4d}/\tau_{3d})$. The ordinate of Fig. 3 was adjusted so that the calculated cascading at foil positions near $l=0$ agreed approximately with the observed cascading in Fig. 1. The sum of the two cascade transitions contributes to the complex cascading into the $2p$ level. The dependence of this sum on foil position is indicated by the curve labeled $\tau_{3d}+\tau_{4d}$. The broken line in Fig. 3 would be the single straight line fitted to the sum of the cascade contributions over the same limited range of foil positions as that used previously to determine $\tau_c$ in the data of Fig. 1. As can be seen in Fig. 3, the straight line is a good approximation for the magnitude of the complex cascading processes into the $2p$ level of He II. This straight-line approximation gives a cascade lifetime of $1.3\times10^{-9}$ sec that is in reasonable agreement with the measured value in Fig. 1 of $1.6\times10^{-9}$ sec. If an additional very small cascade contribution from the $5d$ level were also included in Fig. 3, the agreement between the calculated value $\tau_c$ in Fig. 3 and the measured value of $\tau_c$ in Fig. 1 would be even better.

The interpretation presented above and illustrated in Fig. 3 for the cascading process indicates that the simple cascade correction applied to the experimental data for the emission line He II 304 Å does not introduce an appreciable error in the determination of the mean life of the $2p$ level in He II. A graphical estimate of this error is less than $\pm1\%$. This error is included in the total experimental error given in Fig. 1 and Table I.

The weak cascading into the $3p$ level of the He II, which is evident in the decay of the 256 Å emission line, is assumed to originate predominantly from the $4d$ and $5d$ levels since the lifetimes of these levels are closest to that of the $3p$ level. One would expect the cascading to be weak because the branching fractions for the transitions $3p$-$4d$ and $3p$-$5d$ are only about 0.25. The branching fraction for the transition $3p$-$4s$ is also appreciable (0.42), but, because of the longer mean life of the $4s$ level, this cascading transition is probably not too important. Also, if it is assumed that the upper levels of the ion are populated approximately in accordance with their statistical weights, the initial population of the $4s$ level will be considerably less than the populations of the $4d$ and $5d$ levels. When this complex cascading process is approximated by a single straight line, as in Fig. 2, a lifetime $\tau_c$ having a value between the range of mean lives of the upper cascading levels $4d$, $5d$, and $4s$ (see Table I) will be obtained. Within the limits of experimental error for $\tau_c$, indicated in Fig. 2, the measured value of $\tau_c$ is consistent with a straight-line approximation for this complex decay scheme.

In summary, the experimental values of the mean lifetimes of the $2p$ and $3p$ levels in He II agree with the theoretical values. The observed cascading into the $2p$ and $3p$ levels also agrees with the theoretically predicted cascading from a few of the lower excited levels of He II. The agreement between the measured and theoretical cascading in He II indicates that cascading processes into the upper level of an emission line can be correctly identified, provided that the cascading lifetimes are significantly different from the lifetime of the upper level of the line. Reasonable corrections for cascading can therefore be applied to the decay of the emission line to obtain an accurate experimental value of the mean life of the upper level of the line.