Atomic Lifetimes in Neon I†

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Mean lives of a number of electronically excited atomic levels in Ne I have been determined using a method of delayed coincidence. Following a detailed description of the experimental procedure and a discussion of a series of trial runs in He I, the measured values of the mean lives of the $2p_1$ through $2p_9$, $3p_1$, $3p_{10}$, and $4d_1'$ (Paschen notation) levels in neutral neon are given. These lifetimes, determined from transitions with associated wavelengths extending from ≈3400 to ≈6400 Å, ranged in value from ≈14 to ≈500 nsec. The lifetimes were estimated to contain possible systematic errors varying from 5 to 20% and are presented in comparison with corresponding results of other workers.

INTRODUCTION

THE study of available material[1] on the values of transition probabilities in neon I reveals large discrepancies in results reported by different authors for the $3s$-$3p$ transition array. In an effort to resolve these discrepancies, the experiment being reported on here, the measurement of the mean lives of the $3p$ levels in Ne I, was undertaken. This work is a part of the present effort of the National Bureau of Standards to compile reliable f values for important lines of lighter elements. Portions of this work have been the subject of several preliminary reports.[2–4]

EXPERIMENTAL METHOD AND APPARATUS

Mean lives of a number of excited states in Ne I have been determined using a method of delayed coincidence first applied to atomic lifetime measurement by Heron *et al.*[5] and further developed by Bennett *et al.*[6,7] Figure 1 shows a block diagram of the experimental setup. A pulsed beam of electrons is used to excite atoms of the gas. The excitation pulse also starts a time-to-pulse-height converter. Light pulses from the decay of the excited state pass through a monochromator and strike a photomultiplier. The ensuing pulse from the photomultiplier stops the time-to-pulse-height converter. The converter then feeds a voltage pulse proportional to the time between "Start" and "Stop" into a multichannel pulse-height analyzer. A distribution of decay times is thus built up in the analyzer. This distribution, which is ideally a single exponential, is then used to determine the mean life of the level of interest.

The time-to-pulse-height converter used here is a modification of a high-speed switching and timing device developed by Culligan and Lipman.[8] The range, which can be varied from 15 nsec to 1 μsec, was set at 630 nsec for this experiment. This value was chosen to provide a range several times greater than anticipated maximum lifetimes of interest. The electron gun, a multistage device developed by Simpson and Kuyatt,[9] provided dc beams up to 100 μA in the 20–100-eV energy range. Retarding voltage measurements of the pulsed electron beam have shown an energy spread of $\lesssim$0.5 eV for typical conditions of operation. In operating the electron gun the beam was first cut off by applying a negative voltage to the gun grid. Positive pulses of voltage greater than the negative grid cutoff were then superimposed on the grid allowing bursts of electrons to emerge from the gun. These positive pulses had rise and fall times $\lesssim$1 nsec with variable widths from 5 to 100 nsec. The pulse repetition rate was 2 kc/sec.

The monochromator used here had a speed of $f/4.4$ and a dispersion of 16.5 Å per mm when equipped with either of two interchangeable gratings blazed at 5000 and 7500 Å. A 6256B high-gain, low-dark-current photomultiplier was used to detect the low-intensity light pulses from the atomic decays. A low-dark-current tube was necessary here since dark-current electrons from the photomultiplier give pulses indistinguishable from signal pulses. Adequate signal-to-noise ratios were maintained for the transitions considered here without

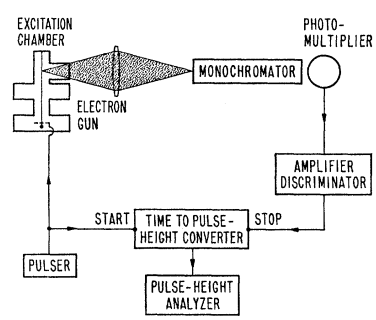

FIG. 1. Block diagram of the experimental setup.

† Work supported in part by Project DEFENDER, sponsored by the Advanced Research Projects Agency, Department of Defense, through the U. S. Office of Naval Research.

[1] B. M. Glennon and W. L. Wiese, Natl. Bur. Std. (U. S.) Monograph 50 (1962), p. 29.
[2] J. Z. Klose, Bull. Am. Phys. Soc. **9**, 425, 606 (1964).
[3] J. Z. Klose, Astrophys. J. **141**, 814 (1965).
[4] J. Z. Klose, Bull. Am. Phys. Soc. **10**, 455 (1965).
[5] S. Heron, R. W. P. McWhirter, and E. H. Rhoderick, Proc. Roy. Soc. (London) **A234**, 565 (1956).
[6] W. R. Bennett, Jr., A. Javan, and E. A. Ballik, Bull. Am. Phys. Soc. **5**, 496 (1960).
[7] W. R. Bennett, Jr., in *Advances in Quantum Mechanics*, edited by J. Singer (Columbia University Press, New York, 1961), p. 28.
[8] G. Culligan and N. H. Lipman, Rev. Sci. Instr. **31**, 1209 (1960).
[9] J. A. Simpson and C. E. Kuyatt, Rev. Sci. Instr. **34**, 265 (1963).

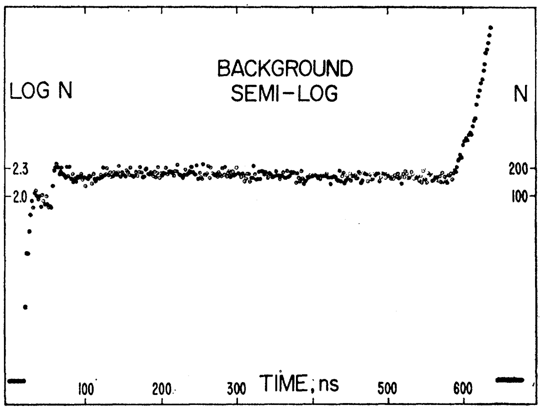

FIG. 2. The log of the number of occurrences at a given time delay plotted versus the time delay for a background run.

recourse to phototube cooling. The converter output pulses were stored in a 400-channel transistorized pulse-height analyzer. Time calibration of the system was effected by providing known time delays between the "Start" and "Stop" pulses in terms of accurately measured lengths of coaxial cable. Two independently measured sets of cables were used in arriving at a value of 1.70 ± 0.05 nsec per analyzer channel as the system time calibration.

The gas samples used were Linde reagent grade in Pyrex bulbs. With a system residual pressure of $\approx 2 \times 10^{-7}$ Torr and operating pressures in the 1–20 μ of Hg range, no further purification of the specimen gases was carried out.

An important requirement to the validity of the experimental method is the absence of any bias in the system in the detection of time delays; that is, there should be equal probability of measuring any time delay throughout the range of the converter. Figure 2 shows a machine plot of a background run with "Stop" pulses coming solely from the dark current of the photomultiplier. The ordinate is the number of occurrences at a given time delay, and the abscissa is the time delay. Each one of the points represents the log of the number of counts stored in a particular channel of the analyzer. It can be seen that over most of the range the number of counts per channel is uniform, indicating no systematic bias in the recording of time delays. Apparent fluctuations appearing in this run were regarded as statistical in nature since the identical fluctuations failed to appear in subsequent background runs. The sharply rising distribution appearing at the long-delay end of the plot arises from "Start" pulses for which no "Stop" pulses are received within the range of the converter.

DELAYED-COINCIDENCE ANALYSIS

In analyzing a delayed coincidence curve to obtain the characteristic mean life of an atomic level, one or more of the methods summarized by Bay[10] may be applicable depending on the shape and parameters of the curve in question. The methods are: (1) the moment method, (2) the slope method, (3) the area method, and (4) the tail method. Each of the above methods involves a knowledge of the time-response curve of the system. The time-response curve, which is also referred to as the prompt-coincidence curve, is established by determining the delayed-coincidence curve for simultaneous pairs of events. In the present application of the delayed-coincidence technique the prompt curve can also be determined by detecting atomic decays whose mean lives are shorter than the intrinsic mean life of the system. A search for such fast decays was carried out in He I and Ne I with negative results within the limitations of the experimental setup. Thus, it was necessary to try to establish the prompt curve through simultaneous pairs of events. This was attempted using a mercury-capsule light-pulse generator[11] which is known to supply simultaneously rising (for the requirements of the present work) light pulses and electrical trigger pulses. Referring to Fig. 1, the mercury-capsule trigger pulses were used to start the time-to-pulse-height converter, while the concurrent light pulses, attenuated to simulate photons from atomic decays,[12] were used to stop the converter. Both the trigger and light pulses had rise times $\lesssim 0.5$ nsec. The width of the light pulses determined by the length of charging line used in the pulser was 2.3 nsec.

Figure 3 shows a linear plot of a "prompt" run obtained with "Start" and "Stop" pulses supplied by a mercury-capsule pulse generator. Examination of the main excitation peak at the left side of the plot shows that the peak is nonsymmetric with a faster rise than fall. These fast-decay curves can be used in establishing

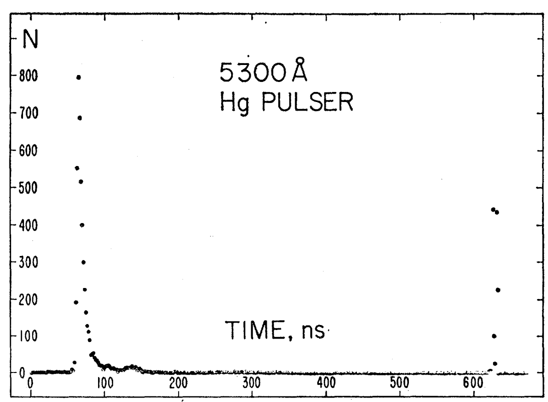

FIG. 3. The number of occurrences at a given time delay plotted versus the time delay for a "prompt" run obtained with a mercury-capsule light-pulse generator.

[10] Z. Bay, IRE Trans. Nucl. Sci. **3**, 19 (1956).
[11] Q. A. Kerns, F. A. Kirsten, and G. C. Cox, Rev. Sci. Instr. **30**, 31 (1959).
[12] R. F. Tusting, Q. A. Kerns, and H. K. Knudsen, University of California Radiation Laboratory Report UCRL-9980, 1962 (unpublished).

an upper limit on the minimum lifetime measurable by the system. Analysis of runs similar to the one shown in Fig. 3 have established the full width at half-maximum of the prompt curve to be <5 nsec. In addition, exponentials fitted to these fast-decay curves had mean lives in the 4–5 nsec range. Thus from these measurements it is concluded that the time resolution of the system is $\lesssim 5$ nsec. (In Fig. 3 the minor peaks arise from after-pulsing of the light which could not be completely suppressed, and the sharp peak at the long-delay end of the plot is the distribution resulting from "Start" pulses for which no "Stop" pulses are received within the range of the converter.)

With information at hand on the upper limit of the time resolution of the system it is now possible to proceed to the consideration of the method to be used in the analysis of the delayed-coincidence curves. Since a highly precise determination of the prompt-coincidence curve was not achieved here due to the non-negligible width of the light pulse, methods 1, 2, and 3 as enumerated above could not be reliably applied in the analysis of the decay curves. However, the requirement for the use of method 4, the fitting of an exponential to the tail of the delayed-coincidence curve, is merely that the width of the prompt curve be less than the mean lives to be measured.[10] Consequently, the tail method is seen to be valid in this experiment for the determination of lifetimes greater than 5 nsec and is therefore utilized in evaluating the mean lives of the atomic states of interest here.

HELIUM MEASUREMENTS

Preliminary to embarking on the program of lifetime measurements in Ne I, an effort was made to test the experimental setup by measuring previously determined lifetimes of states in He I. Measurements were made of the mean lives of the 3^1P and 3^3P levels in He I utilizing the $3^1P \rightarrow 2^1S$ (5016-Å) and $3^3P \rightarrow 2^3S$ (3889-Å) transitions. The procedure for carrying out and analyzing the helium runs was similar to that described elsewhere in this paper for the neon runs with one important exception: The lifetime of the 3^1P level showed a pronounced pressure dependence over the pressure range of 1 to 20 μ of Hg. This pressure dependence was interpreted as being due to imprisonment of the 537-Å ($3^1P \rightarrow 1^1S$) resonance line in helium as reported by other workers.[5] Utilizing the Holstein theory of the imprisonment of resonance radiation,[13,14] the mean life of the 3^1P level was determined for the case of complete imprisonment of the 537-Å line. A value of 78 ± 5 nsec was obtained here to be compared with the value obtained from the highly accurate theoretical calculations of Schiff and Pekeris[15] and Weiss.[16] Schiff and Pekeris used variational wave functions containing up to 220 terms to arrive at a value of 0.1338×10^8 sec^{-1} as the transition probability of the $3^1P \rightarrow 2^1S$ (5016-Å) transition. A value of 0.00253×10^8 sec^{-1} was obtained as the transition probability of the $3^1P \rightarrow 3^1S$ (7435-Å) transition by Weiss using wave functions containing 54 terms. These two transition probabilities when combined give a mean life of 73.4 nsec for the 3^1P level. This value is seen to be in agreement with the experimental value of 78 ± 5 nsec given above.

In contrast with the 3^1P level the lifetime determinations involving the 3^3P level exhibited no pressure dependence over the pressure range of 1 to 20 μ of Hg. Thus, a series of measurements at 3889 Å yielded directly the lifetime of the 3^3P level which turned out to be 97 ± 4 nsec. Calculations similar to those above of Schiff and Pekeris[15] and Weiss[16] give for the $3^3P \rightarrow 2^3S$ (3889-Å) and $3^3P \rightarrow 3^3S$ (42 947-Å) transitions respectively transition probabilities of 0.09478×10^8 sec^{-1} and 0.0108×10^8 sec^{-1}. These two values combine to yield a mean life of 94.7 nsec for the 3^3P level in helium. Thus, it can be concluded from the agreement of the experimental and theoretical determinations in helium given here that the present experimental setup is capable of producing reliable values of atomic lifetimes.

ANALYSIS

Figures 4 and 5 show typical examples of runs used in the lifetime determinations carried out in this work. Figure 4 is a semilog plot of the $2p_1 \rightarrow 1s_2$ (Paschen notation) transition in Ne I showing essentially a single exponential decay. This run with a maximum in the excitation peak of about 5000 counts and an average background of about 50 counts has a signal-to-background ratio of 100/1. Since little useful information was obtained from runs with such ratios less than 20/1, only runs with signal-to-background ratios greater than this value were used in arriving at the lifetime results reported here. A run such as the one shown in Fig. 4

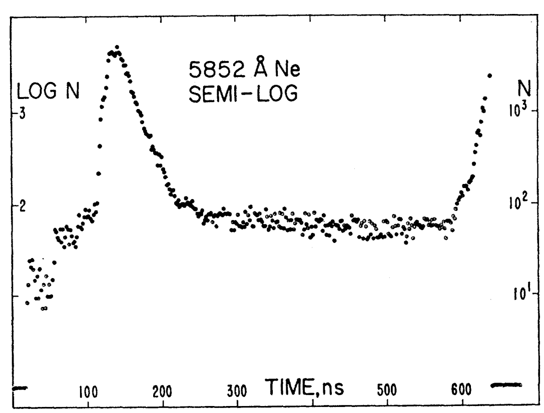

FIG. 4. The log of the number of occurrences at a given time delay plotted versus the time delay for a run involving the $2p_1 \rightarrow 1s_2$ transition in Ne I.

[13] T. Holstein, Phys. Rev. **72**, 1212 (1947).
[14] T. Holstein, Phys. Rev. **83**, 1159 (1951).
[15] B. Schiff and C. L. Pekeris, Phys. Rev. **134**, A638 (1964).
[16] A. W. Weiss (to be published).

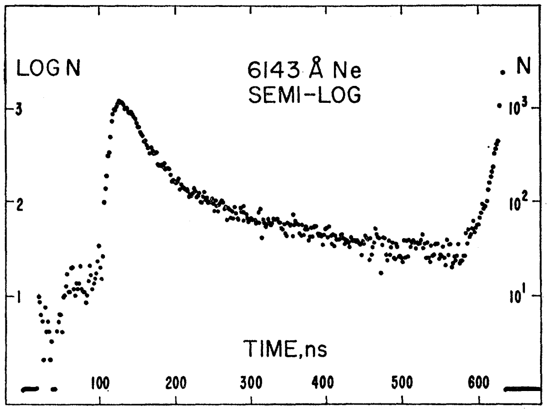

FIG. 5. The log of the number of occurrences at a given time delay plotted versus the time delay for a run involving the $2p_6 \rightarrow 1s_5$ transition in Ne I.

permits a precise determination of the mean life from the semilog plot alone. However, in routine operation of the experiment a computer program fitting two exponentials and a background to the raw data was used to evaluate the lifetimes. Spot comparisons of direct plot determinations and computer determinations showed excellent agreement.

For most spectral lines decay curves as obtained under the conditions of this experiment cannot be limited to single exponentials. The run shown in Fig. 5 ($2p_6 \rightarrow 1s_5$ transition in Ne I) is an example of a two-exponential decay. In this plot the rapidly decaying component is regarded as being due to the direct excitation of the $2p_6$ level. The secondary and more slowly decaying component is attributed to cascading from some simultaneously excited higher level feeding into the $2p_6$ level. In principle cascading can be eliminated by decreasing the electronic excitation energy until the electron energy is less than that sufficient to excite the upper levels but still high enough to excite the level of interest. This approach was not adopted here for two reasons: (1) The electron-beam energy spread was often greater than the energy separation between the higher levels involved in the cascading and the level of interest, and (2) at sufficiently low electron energies the excitation cross section of the level of interest was too small to provide adequate signal-to-background ratios. In practice the procedure utilized was to optimize the direct-excitation signal-to-background ratio by varying the electron energy. The electron energy was then reduced gradually as much as possible without producing a significant decrease in the signal-to-background ratio. This procedure resulted in excitation energies in the 20–30-eV range for the levels in neon treated here. The above procedure could not completely eliminate the effects of excitation by cascading. However, the effects of cascading were minimized by accepting only runs with a secondary exponential having a lifetime at least 10 times that of the primary exponential. In a given run this requirement resulted in the manifestation of the cascading effect as an easily separable secondary exponential if the lifetime of the cascading level was significantly longer than that of the level of interest. If the lifetime of a cascading level was approximately equal to that of the level of interest, significant errors could be introduced in the measured lifetime. It was estimated theoretically by using the Coulomb approximation[17] that for most of the transitions investigated here the lifetimes of the important cascading levels were significantly longer than the lifetimes of the levels of interest.

A second source of multiple exponentials in a decay curve may be the simultaneous passage of more than one spectral line through the low-resolution monochromator. The maintenance of adequate signal-to-background ratios prevented narrowing the monochromator slits sufficiently to ensure the isolated passage of the spectral line of interest. However, for most of the transitions studied in this experiment the associated spectral line was sufficiently separated from nearby stronger or comparably strong lines as to be the overwhelmingly predominant wavelength transmitted by the monochromator. In the single instance encountered here when two comparably strong lines (5975 and 5976 Å) were transmitted simultaneously, it was possible to utilize the isolated line of an alternative transition from the same upper level (6128 Å) to obtain the desired decay curve.

In summary, the criteria for acceptance of runs to be used in this work were: (1) Each run must have a maximum of at least 1000 counts in the excitation peak; (2) the ratio of the maximum number of counts in the excitation peak to the average number of counts in the background must be $\geq 20/1$; (3) the data must be amenable to a least-squares computer fit of a primary exponential, a secondary exponential, and a background; and (4) the secondary exponential obtained in the computer analysis must have a mean life ≥ 10 times that of the primary exponential.

RESULTS

Table I gives the results of the present work with determinations of other workers for comparison. In arriving at the final value of the lifetime for each of the states, runs were made over a range of pressures from 1 to 20 μ of Hg with excitation pulse widths varying from 5 to 20 nsec. No dependence of lifetime on either pressure or excitation pulse width was detected for the transitions treated here. (Pressure effects of possible importance here could be either competing collisional decay or radiative imprisonment. However, approximate calculations utilizing the Holstein theory[13,14] rule out the presence of radiative imprisonment in the neon

[17] D. R. Bates and A. Damgaard, Phil. Trans. Roy. Soc. (London) **A242**, 101 (1949).

TABLE I. Values of mean lives of atomic levels in neon I.

Level (Paschen notation)	Transition	λ Å	Present work	Systematic error	Mean life in nanoseconds Lad.[a]	Griff.[b]	Osh.[c]	McL.[d]	P.-T.[e]	Doh.[f]	Koop.[g]	Fried.[h]	Coulomb approx.[i]
$2p_1$	$2p_1 \rightarrow 1s_2$	5852	14.7±0.6	5%	8	39	51	3.8	...	28	17.7	17	15.3
$2p_2$	$2p_2 \rightarrow 1s_5$	5882	16.3±0.6	5%	10	...	...	<50	<24.0	31	21.0	...	...
$2p_2$	$2p_2 \rightarrow 1s_3$	6164	16.8±0.7	10%	10	...	...	<50	<24.0	31	21.0	...	...
$2p_3$	$2p_3 \rightarrow 1s_4$	6074	23 ±2	20%	12.5	...	...	5	10.8	31	21.3	17	17.0
$2p_4$	$2p_4 \rightarrow 1s_4$	6096	22 ±1	20%	12	85	...	...	<29.8	40	24.5	...	...
$2p_4$	$2p_4 \rightarrow 1s_5$	5945	23 ±2	20%	12	80	110	...	<29.8	40	24.5	...	...
$2p_5$	$2p_5 \rightarrow 1s_4$	6128	18.9±0.9	10%	>10.4	...	...	<11	<34.5	40	<24.9	...	...
$2p_6$	$2p_6 \rightarrow 1s_5$	6143	22 ±1	10%	13	90	115	<20	<45.7	40	25.8	...	...
$2p_7$	$2p_7 \rightarrow 1s_4$	6383	20.3±0.6	10%	13	...	...	...	18.4	37	24.8	...	...
$2p_8$	$2p_8 \rightarrow 1s_5$	6334	24.3±0.8	10%	16	115	109	<24	<30.4	43	27.6	...	...
$2p_9$	$2p_9 \rightarrow 1s_5$	6402	22.5±0.9	10%	17	200	...	...	33.1	34	23.3	...	19.9
$3p_1$	$3p_1 \rightarrow 1s_2$	3520	63.5±0.7	5%	...	...	...	...	...	...	...	...	...
$3p_{10}$	$3p_{10} \rightarrow 1s_4$	3563	65 ±3	10%	...	...	...	...	...	...	...	...	...
$4d_1'$	$4d_1' \rightarrow 2p_6$	5975	480±30	20%	...	...	...	...	...	...	...	...	...

[a] R. Ladenburg and S. Levy, Z. Physik **88**, 461 (1934).
[b] J. H. E. Griffiths, Proc. Roy. Soc. (London) **A143**, 588 (1934).
[c] A. L. Osherovich and G. M. Petelin, Dokl. Akad. Nauk SSSR **129**, 544 (1959) [English transl.: Soviet Phys.—Doklady **4**, 1289 (1960)].
[d] E. A. McLean, in *Proceedings of the Sixth International Conference on Ionization Phenomena in Gases, Paris* (Paris, 1963), Vol. III, p. 389.
[e] A. Pery-Thorne and J. E. Chamberlain, Proc. Phys. Soc. (London) **A82**, 133 (1963).
[f] L. R. Doherty, Ph.D. thesis, University of Michigan, Ann Arbor, 1962 (unpublished).
[g] D. W. Koopman, J. Opt. Soc. Am. **54**, 1354 (1964).
[h] H. Friedrichs, Z. Astrophys. **60**, 176 (1964).
[i] D. R. Bates and A. Damgaard, Phil. Trans. Roy. Soc. (London) **A242**, 101 (1949).

measurements of this work.) Ten or more runs at each wavelength were used in determining the values of the mean lives. The error given with each lifetime is its probable error computed from the dispersion of the individual measurements. An adjoining column lists the estimated possible systematic errors. The $2p_1$ and $2p_2$ levels whose mean lives were determined from runs typical of the one shown in Fig. 4 are assigned systematic errors of 5% each due to possible local nonlinearities in the time scale of the system. Lifetimes of levels $2p_3$ through $2p_9$ were determined from runs similar to the one shown in Fig. 5. The tabulated systematic errors for these states are based for the most part on estimates of the effects of cascading on the values of the lifetimes but also include the 5% contribution of possible local nonlinearities in the time scale of the system. The lifetimes of levels $2p_2$ and $2p_4$ were each determined from two separate transitions originating from the level in question. The pairs of values obtained for those two levels are seen to be in complete agreement giving a good indication of the internal consistency and precision of the experimental method.

Measurements involving the $2p_{10}$ level were not accomplished since all transitions from this level have wavelengths longer than the 6500-Å long-wavelength cutoff of the employed S-13 photomultiplier. Examples of runs of the remaining levels are not given here. It should be mentioned, however, that plots of runs involving transitions from the $3p_1$ and $3p_{10}$ levels show scant evidence of a secondary exponential.

In Table I the sets of lifetime values labeled Ladenburg[18] and Pery-Thorne were each obtained by a method of anomalous dispersion, the Roschdestwensky "hook" method.[19,20] The values given by Griffiths and Osherovich were arrived at through direct lifetime measurements, whereas the measurements of McLean and Doherty were made in emission from shock-tube sources. The results of Friedrichs were also obtained in an emission experiment but from a stabilized arc source. The tabulation due to Koopman was obtained by means of an f-sum-rule adjustment of Doherty's results. Finally, values derived by means of the Coulomb approximation of Bates and Damgaard are given for three levels for which experimental evidence indicates one dominant decay possibility.

In comparing the values of this experiment with the results of other workers, the following points become evident. The values given by Ladenburg are in every case smaller than those of the present work, whereas the values given by Doherty are in every case larger. The adjustment of Doherty's results carried out by Koopman gives values generally larger than those of the present work but in better agreement than either the Ladenburg or Doherty tabulations. The values given by Friedrichs show general agreement with the present work as do the values obtained from the Coulomb approximation. However, the results of Ladenburg, Doherty, Koopman, and the present work do show one common characteristic: The relative scales of lifetime values are nearly identical for each of the four tabulations. This similarity of the relative scales is not unexpected in the results of Ladenburg, Doherty, and Koopman since the determinations of these workers are known to be capable of giving reliable sets of relative

[18] References not otherwise given to authors cited in this and following paragraphs are given in footnotes to Table I.

[19] D. Roschdestwensky, Ann. Physik **39**, 307 (1912).

[20] D. Roschdestwensky, Trans. Opt. Inst. Len. **2**, No. 13 (1921).

values. The agreement of the relative scale of the present work with those of the three previous workers is, therefore, another indication of the internal consistency of the results of the present work.

A perplexing point is the disagreement of the Griffiths and Osherovich results with those of this experiment. Among the results of other workers presented in Table I, only those of Griffiths and Osherovich were obtained by direct lifetime measurements. It is seen, however, that the values of these two workers are much larger than the corresponding values of the present work. Upon examination of the descriptions of their experiments, a point of variance with the present experiment is noted: The minimum lifetimes measured with both the Griffiths and Osherovich experimental setups were much greater than the minimum lifetime measured here (Griffith, 39 nsec, and Osherovich,[21] 33 nsec, as compared with the present work, 5 nsec). Thus, it seems possible that the disagreement in the direct lifetime measurements could arise from the inability of the Griffiths and Osherovich experimental setups to measure short enough lifetimes. However, since relevant experimental details of the two previous experiments are unpublished, the discrepancies remain basically unresolved.

[21] A. L. Osherovich and I. G. Savich, Opt. i Spektroskopiya 4, 715 (1958).

ACKNOWLEDGMENTS

The author wishes to thank Dr. W. L. Wiese and Dr. Z. Bay for a number of valuable discussions. Thanks are also in order to Dr. D. C. Schubert for collaboration in the development of the computer program.

Note added in proof. Since this manuscript was submitted, delayed-coincidence determinations by Bennett *et al.*[22] of the lifetimes of several $2p$ (Paschen notation) levels in Ne I have come to the attention of the author. The mean lives in nanoseconds given by these workers are as follows: $2p_1$, 15 ± 1; $2p_2$, 19 ± 2; $2p_4$, 19 ± 1; and $2p_6$, 29 ± 12.

[22] W. R. Bennett, Jr., P. J. Kindlmann, and G. N. Mercer, Appl. Opt. Suppl. 2, 34 (1965).

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Stochastic Acceleration*

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Charged particles moving under the influence of randomly time-varying electromagnetic fields may be expected to experience a net acceleration. This process is analyzed for the special case of nonrelativistic motion in a static uniform magnetic field and time-varying electric field. Acceleration parallel and transverse to the magnetic field are considered separately. In the weak-field approximation, the motion may be described by a Fokker-Planck equation. The coefficients of this equation are expressible in terms of the correlation functions for the electric fields. In certain cases, the coefficients may be expressed in terms of the energy spectrum of the field. The Fokker-Planck equation derived for motion along the magnetic field is closely related to an equation of the quasilinear theory of plasma instability. One may also show that the equation is closely related to the phenomenon of Landau damping. Longitudinal acceleration is effected by waves with phase velocities slightly greater than the particle velocity. A similar statement is true for transverse acceleration, except that the "resonant" waves are in addition shifted by the particle gyrofrequency. In the absence of any other effects (such as "loading" of the accelerating field by the accelerated particles), the transverse energy distribution tends to a Maxwellian form with a temperature which increases linearly with time. The same is true for longitudinal acceleration if the spectrum of the electric field is flat over the range of phase velocities of interest. The equations related to transverse acceleration show that the high-energy electrons observed in the transition region outside the earth's magnetosphere may have been accelerated by quite weak random or quasirandom electric fields.

I. INTRODUCTION

THERE is good reason to try to understand the mechanisms by which charged particles may be accelerated in random electromagnetic fields. Laboratory experiments have shown that electrons may be accelerated to high energy by the electric field generated by a beam-plasma instability.[1,2] Spacecraft experiments have shown that high-energy electrons are produced in the transition region between the magnetosphere and the bow shock.[3,4] It has been proposed by Bernstein,

* Work sponsored by the National Aeronautic and Space Administration under Grant NsG-703.

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