results. We have measured the polarization as a function of magnetic field at various electron-beam energies corresponding to the values previously reported. However, we found no dependence of the polarization on the magnetic field up to 30 G for the lines reported in this paper. This is of course what one expects theoretically. It also confirms the suggestion by McFarland[1] that the previously reported results are fallacious and can be explained in terms of wall effects. It is to be remembered that the vacuum chamber used in these experiments is much larger than that used in the previous measurements.

CONCLUSION

Our results on the polarization from helium bombarded by slow electrons are in reasonable agreement with the results reported by McFarland. Also, the polarization of light shows no dependence on the strength of the magnetic field parallel to the electron beam.

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Radiative Lifetimes for uv Multiplets of N II through N V

L. HEROUX
Air Force Cambridge Research Laboratories, Bedford, Massachusetts

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The foil-excitation technique has been used to measure radiative lifetimes of eighteen uv multiplets in N II through N V. The multiplets were produced by passing a N^+ beam of known energy through a thin carbon foil that could be moved in small steps along the axis of the beam. The beam energy was either 1 or 2 MeV and the foil thickness either 500 or 1000 Å. A grazing-incidence monochromator instrumented for photoelectric counting was used to measure the decay of the multiplet as a function of distance downstream from the intersection of the foil and beam. The wavelengths of the measured multiplets were from 1085 Å (N II) to 162 Å (N V). Most of the multiplets were transitions to the ground-term configuration. The mean lifetimes range from about 3×10^{-9} to 0.5×10^{-10} sec, the measured accuracy being between 5 and 15%. Corrections for cascading were necessary for many of the multiplets. Transition probabilities obtained from the lifetime measurements are compared with other experimental and theoretical determinations.

I. INTRODUCTION

ONE experimental method to obtain lifetimes of excited states of an atomic system utilizes the foil-excitation technique.[1,2] A monoenergetic ion beam is passed through a thin foil which serves to create multiple ionization of the incident beam and also to excite the ions. The emergent ion beam, therefore, contains a mixture of ion species, having known velocities, in various states of excitation. If cascades into the excited levels are negligible, a measurement of the decay of a transition from the excited level as a function of distance downstream from the intersection of the foil and beam gives a direct measurement of the lifetime of the upper level. Because the density of the ion beam usually is extremely low, the excited levels will not be subjected to any appreciable external influences such as Stark-effect broadening, and the measured lifetime will be essentially that of an isolated atom. Reabsorption of the emitted radiation also will be negligible because of the low ion densities. Cascading into the upper levels often occurs, but if the cascading lifetimes are either significantly different from the lifetime of the excited level or the cascading transitions into the excited level do not contribute significantly to the population of the level, reasonable corrections for cascading usually can be made. When only one transition occurs from the excited term, the lifetime measurement is also a direct measurement of the transition probability for the transition.

Several measurements of lifetime have been obtained recently with the foil-excitation technique. Bashkin *et al.*[3] obtained an estimate of the lifetimes of the $2p^4\,{}^2D$ term of Ne IV and the $2p^2\,{}^2D$ term of Ne VI by measuring the decay of the multiplets Ne IV 470 and Ne VI 561 at two positions along the ion beam. This experiment illustrated that the foil-excitation technique could be used to measure lifetimes as short as 10^{-10} sec from the observation of multiplets in the uv with fairly good spectral resolution (approximately 3-Å bandpass) and good spatial resolution along the length of the ion beam. Berkner *et al.*[4] measured the transition probabilities of the $2s$-$2p$ transitions in the ions of the Li-like sequence between C IV and Ne VIII by observing the decay of the uv resonance multiplets with a vacuum monochromator having a bandpass of 32 Å. Bickel and Bashkin[5] obtained the lifetime of the $2p^2\,{}^1D_2$ level in O V by monitoring the decay of the emission line of O V at 1371 Å

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[1] L. Kay, Phys. Letters **5**, 36 (1963); Proc. Phys. Soc. (London) **85**, 163 (1965).

[2] S. Bashkin and A. B. Meinel, Astrophys. J. **139**, 413 (1964).

[3] S. Bashkin, L. Heroux, and J. Shaw, Phys. Letters **13**, 229 (1964); S. Bashkin, R. K. Wangsness, and L. Heroux, Phys. Rev. (to be published).

[4] K. H. Berkner, W. S. Cooper III, S. N. Kaplan, and R. V. Pyle, Phys. Letters **16**, 35 (1965).

[5] W. S. Bickel and S. Bashkin, Phys. Letters **20**, 488 (1966).

with a vacuum monochromator having an instrumental linewidth of 16 Å. The lifetimes of the fine structure states of the $n=3$ and $n=4$ levels in hydrogen were measured by Goodman and Donahue,[6] who observed the decay of H_α and H_β which were isolated with interference filters.

The foil-excitation technique is particularly useful for measurements of lifetimes of the multiply ionized atomic species abundant in many laboratory and astrophysical plasmas. Often the most intense transitions to the ground term lie in the vacuum ultraviolet. In the present experiment, the lifetimes of several terms in N II through N V were determined by observing the decay, along the ion beam, of various uv multiplets in the wavelength range 162–1085 Å. The multiplets were observed with a grazing incidence monochromator having an instrumental resolution of either 0.5 or 2 Å, depending upon the wavelength region. Because the lifetimes are generally short, the multiplets decay rapidly with increasing distance from the foil. To obtain good spatial resolution of this decay, the instrumental viewing length of the monochromator along the ion beam was kept small and the foil moved along the beam in small accurate steps. The combination of moderately high spectral resolution and good spatial resolution results in low signal levels for the multiplets. Photon-counting techniques were used to measure these low signal levels.

II. APPARATUS

The experimental arrangement is shown schematically in Fig. 1. A mass-analyzed N^+ ion beam, produced with a 3-MeV Van de Graaff accelerator, was passed through a thin self-supporting carbon foil. The energy of the incident beam was either 1 or 2 MeV and the foil thickness either 10 $\mu g/cm^2$ or 20 $\mu g/cm^2$, thicknesses of about 500 Å and 1000 Å, respectively. The direction of the ion beam was perpendicular to the plane of the foil (6.5 mm in diam), and the emission spectrum of the ion beam was viewed at 90° to the beam direction with a grazing incidence vacuum monochromator which covered the wavelength range 60–1250 Å. The pressure in the foil chamber and in the monochromator was always less than 10^{-5} mm Hg. Multiplets of N II through N V were observed which established that at least the ions N^+ to N^{4+} were produced by the interaction of the beam and foil.

The beam transmitted by the carbon foil was collected on an insulated flange and measured with a microammeter. This measurement of current (approximately 0.8 μA) served only as a monitor on the constancy of the beam current. It did not determine the quantitative value of ion-beam current through the foil, since the geometry of the flange was far from that of a shielded Faraday cup and part of the measured current included secondary electrons ejected from the foil.[3] The fluctuations in the beam current, measured in this manner, were usually less than 5% during the interval of time required to accumulate data for the measurement of lifetime of a particular multiplet.

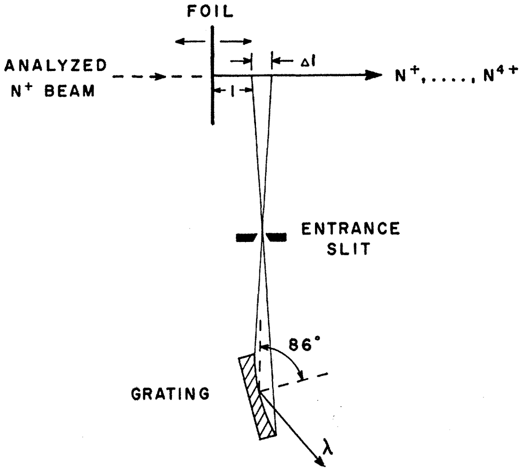

FIG. 1. Experimental arrangement used to observe the emission spectrum of the nitrogen-ion beam.

The viewing length of the monochromator Δl along the direction of the ion beam and in the plane of dispersion of the monochromator was about 1 mm. The carbon foil was moved in steps of 0.04 mm along the axis of the beam by a stepping motor. This enabled the decays from the upper term of a particular multiplet to be measured as a function of distance l from the intersection of the foil and ion beam.

The monochromator was a 2-m grazing incidence instrument employing photoelectron detection. The instrument was similar to a telemetering rocket monochromator described elsewhere.[7] It was modified for laboratory use by mounting in a vacuum chamber, adding a remote wavelength drive, and modifying the pulse-counting instrumentation to operate commercial scalers. Two interchangeable gratings, one with 30 000 lines/in. and one with 7500 lines/in., were used to cover the two ranges of wavelength 60–300 Å and 300–1250 Å. The numerical aperture of the instrument was $f/50$. To obtain reasonable signals, a 100-μ-wide entrance slit was used. Wavelength scanning was accomplished by moving an endless Be-Cu belt with an exit-slit cutout along the Rowland circle. The exit slit was selected so that its effective width in the plane perpendicular to the direction of the diffracted beam overmatched the image of the entrance slit along the entire Rowland circle. A stepping motor drive stepped the belt in increments corresponding to either $\frac{1}{6}$, $\frac{1}{3}$, or $\frac{2}{3}$ the width of the slit. The instrumental linewidth of the monochromator was approximately 0.5 Å for the wavelength range 60–300 Å and about 2 Å between 300 and 1300 Å. The wavelength scale was calibrated using laboratory light sources to

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[6] A. S. Goodman and D. J. Donahue, Phys. Rev. 141, 1 (1966).

[7] H. E. Hinteregger, *Space Astrophysics*, edited by W. Liller (McGraw-Hill Book Company, Inc., New York, 1961), p. 34.

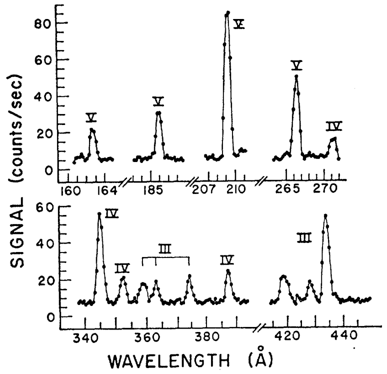

FIG. 2. Counting rate versus wavelength for various sections of the wavelength range obtained with an incident N^+ beam energy of 2 MeV. The upper and lower data were obtained with two different diffraction gratings and two different foils. The foil thicknesses were 500 Å (upper) and 1000 Å (lower). The ionization stages of nitrogen are identified by Roman numerals.

produce several emission lines of known wavelength. Additional calculations using the grating equation and the position of these emission lines permitted calibration[8] of the entire wavelength scale with an accuracy of better than 0.25 Å between 60 and 300 Å, and 1 Å between 300 and 1250 Å.

The detector was a Bendix M 303 magnetic photomultiplier which intercepted the dispersed radiation that passed through the exit slit. The multiplier was operated as a photoelectron counter in the center of its counting plateau.[9] This photon counting system offered the advantages of high sensitivity for wavelengths below about 1200 Å, a low background noise, and a low sensitivity to scattered light of longer wavelength. A background counting rate of about 4 counts/sec was typical with the accelerator operating. Spectral scans of the radiation from the ion beam at a particular foil position l were automatic. Counts were accumulated for a fixed interval of time, the accumulated data printed, the exit slit automatically stepped to the next wavelength position, and the cycle then repeated. For measurements of lifetimes, the monochromator was set at the wavelength of the multiplet and the counts recorded for various foil positions.

The interpretation of the experimental counting rate versus foil position for the emission spectrum of the ion beam, observed in the geometry of Fig. 1, is particularly simple when cascading into the upper terms of the multiplets is neglected. The interaction of the ion beam with the foil produces at the foil a steady-state flux N_p^0 (cm^{-2} sec^{-1}) of a particular ion species excited to term p. If cascades into term p are neglected and if scattering by the foil is also negligible, this flux decreases exponentially with increasing distance l along the ion beam because of radiative transitions out of term p. The flux through a plane which is parallel to the foil and located on the axis of the beam at a distance l downstream from the foil is given by

$$N_p(l)=N_p^0e^{-l/v\tau_p}, \qquad (1)$$

where τ_p is the lifetime of term p, and v is the ion velocity. The counting rate for a particular multiplet corresponding to the transition from upper term p to lower term k, observed in the geometry of Fig. 1, therefore, will be

$$I_{pk}(l,\Delta l)=CN_p^0S(A_{pk}/A_p)[1-e^{-\Delta l/v\tau_p}]e^{-l/v\tau_p}, \qquad (2)$$

where $A_p(=1/\tau_p)$ is the total Einstein transition probability of term p and A_{pk} is the transition probability for the multiplet. S is the area of the foil, and the factor C is the product of a geometrical factor for the monochromator and the photometric efficiency of the monochromator. The factor N_p^0S in Eq. (2) represents the total number of radiative transitions per second from term p which are distributed along the length of the ion beam downstream from the foil. For a constant ion-beam current, this factor also will be constant. The fraction of these transitions which contribute to the multiplet transition p to k is given by the branching fraction A_{pk}/A_p. The relative counting rates for different multiplets, therefore, depend on the parameters l and Δl as well as on the lifetimes of the upper terms of the multiplets. Because of the factor $\Delta l/v\tau_p$, the observed counting rates for multiplets with short decay lengths, $v\tau_p$, observed near the foil will be emphasized in comparison to those multiplets having a longer decay length. This is because a larger fraction of the total number of multiplet transitions, $N_p^0SA_{pk}/A_p$, will occur within the viewing length Δl of the monochromator. For long decay lengths, $\Delta l/v\tau_p \ll 1$, only the small fraction $\Delta l/v\tau_p$ of the total number of radiative transitions will occur within Δl.

III. THE EMISSION SPECTRUM

Spectral scans of the emission spectrum of the nitrogen-ion beam were made only over limited sections of the wavelength range where strong emission lines of N II to N V were known to occur. A search was also made for several uv multiplets of N I, but they were not detectable. The dependence of the intensity of several multiplets of the various stages of ionization on foil thickness and beam energy also was checked. These data were very limited since only two foil thicknesses and two beam energies were used (Sec. II). The multiplets of N II were observed to be more intense for the thin foil (500 Å thick), while the multiplets of N III, IV, and V were nearly the same for the foil thicknesses 500 and 1000 Å. This behavior, which was observed only qualitatively for the two beam energies 1 and 2 MeV, suggests that a carbon foil, 500 Å thick, produces an approximate equilibrium distribution for the various charge states. In addition, the multiplets of N II were

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[8] Dr. L. A. Hall of Air Force Cambridge Research Laboratories suggested this method.

[9] L. Heroux and H. E. Hinteregger, Rev. Sci. Instr. 31, 280 (1960).

TABLE I. Results for N II through N V.

Atom (1)	λ (Å) (2)	Multiplet (3)	τ This experiment (10^{-9} sec) (4)	A_p This experiment (10^9 sec^{-1}) (5)	A_{pk} This experiment (10^9 sec^{-1}) (6)	A_{pk} Other methods (10^9 sec^{-1}) (7)
N II	1085.1	$2p^2\,{}^3P-2p^3\,{}^3D^\circ$[a]	2.92 ±0.15	0.342	0.342	0.37±0.04,[f] 0.57[g]
	916.3	$2p^2\,{}^3P-2p^3\,{}^3P^\circ$[a]	0.96 ±0.05	1.04	1.04	1.8[g]
	645.0	$2p^2\,{}^3P-2p^3\,{}^3S^\circ$[a]	0.11 ±0.01	9.1	9.1	11[g]
	671.5	$2p^2\,{}^3P-3s\,{}^3P^\circ$[b]	1.01 ±0.15	0.99	0.99	1.3[h]
	529.7	$2p^2\,{}^3P-3d\,{}^3P^\circ$[b]	0.53 ±0.05	1.90	1.79[d]	2.0[h]
N III	991.0	$2p\,{}^2P^\circ-2p^2\,{}^2D$[a]	2.40 ±0.24	0.420	0.420	0.73[i]
	685.7	$2p\,{}^2P^\circ-2p^2\,{}^2P$[c]	0.17 ±0.03	5.9	5.9	6.4[i]
	452.1	$2p\,{}^2P^\circ-3s\,{}^2S$[b]	0.40 ±0.06	2.50	2.50	4.5[h]
	374.4	$2p\,{}^2P^\circ-3d\,{}^2D$[c]	0.10 ±0.01	10	10	11[h]
	434.0	$2p^2\,{}^4P-3s\,{}^4P^\circ$[b]	0.26 ±0.04	3.8	3.8	1.6[j]
N IV	923.2	$2p\,{}^3P^\circ-2p^2\,{}^3P$[b]	0.70 ±0.05	1.43	1.43	1.7[k]
	335.1	$2p\,{}^1P^\circ-3d\,{}^1D$[c]	0.050±0.008	20.0	20.0	18.9[l]
	345.1	$2p^2\,{}^3P-3s\,{}^3P^\circ$[b]	0.15 ±0.02	6.7		3.4[j]
	351.9	$2p^2\,{}^1D-3s\,{}^1P^\circ$[b]	0.16 ±0.03	6.3		4.9[j]
N V	209.3	$2s\,{}^2S-3p\,{}^2P^\circ$[c]	0.084±0.008	11.9	11.9	11.95,[m] 11.6[n]
	162.6	$2s\,{}^2S-4p\,{}^2P^\circ$[b]	0.17 ±0.02	5.9	4.5[e]	5.7[j]
	266.2	$2p\,{}^2P^\circ-3s\,{}^2S$[b]	0.12 ±0.02	8.3	8.3	9.05,[m] 9.32[n]
	186.1	$2p\,{}^2P^\circ-4d\,{}^2D$[c]	0.065±0.010	15.4	12.0[e]	14[j]

[a] Cascade-free multiplet.
[b] Weak cascading.
[c] Strong cascading.
[d] Branching fraction from NBS values (see Ref. 15).
[e] Branching fraction from Coulomb approximation (see Refs. 16 and 17).
[f] Measurement of Lawrence and Savage (see Ref. 13).
[g] Calculation of Bolotin *et al.* (see Ref. 18).
[h] Calculation of Kelly (see Ref. 14).
[i] Calculation of Bolotin and Yutsis (see Ref. 19).
[j] Coulomb approximation from tables by Griem (see Ref. 16).
[k] Self-consistent-field (SCF) calculation of Weiss, listed in NBS tables (see Ref. 15).
[l] Hartree-Fock (HF) calculation, P. S. Kelly, J. Quant. Spectry. Radiative Transfer **4**, 117 (1964).
[m] HF dipole-length calculation of Weiss (see Ref. 20).
[n] HF dipole-velocity calculation of Weiss (see Ref. 20).

more intense for the lower beam energy while the multiplets of N IV and N V were significantly stronger for the higher beam energy, indicating that the distribution of the various ionization stages shifted toward higher stages with increasing energy. This general behavior has been observed by others.[1,2]

Figure 2 illustrates typical data for $I(l,\Delta l)$ versus λ for the foil excited spectra of nitrogen viewed near the intersection of the foil and beam. These data were accumulated using a beam energy of 2 MeV ($v=5.3\times10^8$ cm sec^{-1}) and two different foil thicknesses. To reduce statistical fluctuations associated with the low count rates, a 10-sec counting interval was used to obtain the data of Fig. 2. The exit slit was moved two wavelength positions for each measurement merely to reduce the time required for scanning. The various stages of ionization were identified using the tables of Moore[10] and Kelly.[11] Blending of the multiplets can often be identified by a broadened line profile; hence, the broad line near 419 Å is probably due to N III 418.8 Å and a second-order contribution from N V 209.3 Å. Because of the low photometric efficiency of the monochromator at wavelengths longer than about 1100 Å, several important multiplets were undetectable. The $2s$-$2p$ resonance doublet of N V at 1238 and 1242 Å, for example, was not observed, although other multiplets of N V were observed. The detection of this resonance multiplet is difficult also because the factor $\Delta l/v\tau_p$ in Eq. (2) is only 0.06 for the parameters used here. The resonance multiplets of N I at 1200 and 1134 Å may be absent also because of the low photometric efficiency and a small $\Delta l/v\tau_p$, although this is not certain since N I may not be an important constituent of the ion beam after passage through the foil.

IV. MEASUREMENTS OF LIFETIMES

When cascading into an upper-term p is negligible, the experimental counting rate of any multiplet originating from term p will decrease exponentially with increasing distance l with the characteristic lifetime of term p. When cascading does occur, term p is partially repopulated along the length of the ion beam at a rate determined by the lifetime of the upper term of the cascading transitions τ_c. The flux $N_p(l)$ and the measured counting rate $I(l,\Delta l)$ along the beam, therefore, will be a combination of exponential terms having temporal characteristics of τ_p and the cascading lifetimes τ_c.[12] If the cascading transitions into term p have lifetimes significantly different from the lifetime of term p, the data often can be separated into the component

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[10] C. E. Moore, Natl. Bur. Std. (U. S.) Circ. 488 (1950), Sec. 1.

[11] R. L. Kelly, University of California Radiation Laboratory Report No. UCRL 5612, 1959 (unpublished).

[12] D. Halliday, *Introductory Nuclear Physics* (John Wiley & Sons, Inc., New York, 1950), p. 35.

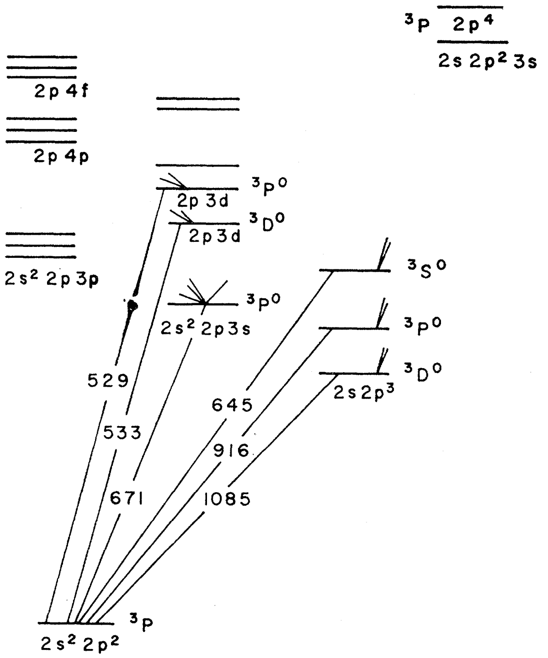

FIG. 3. Partial-term diagram for the triplet system of N II.

lifetimes. An example of this separation is apparent in the measurements of Berkner *et al.*[4] for the transition probabilities of the $2s$-$2p$ transitions of ions in the Li-like sequence. The magnitude of the cascades into the $2p\,{}^2P^0$ term of these ions should be extremely high since the upper terms $ns\,{}^2S$ and $nd\,{}^2D$, $n\geq3$, will decay predominantly into the $2p\,{}^2P^0$ term. Because the cascade lifetimes are much shorter than the lifetime of the $2p$ term, the cascades apparently have essentially terminated at a short distance from the foil, and the decay for longer distances approaches a single exponential characteristic of the lifetime of the term $2p\,{}^2P^0$.

A complex decay curve for I versus l also will occur for blended multiplets, since the components of the blend generally will originate from upper terms having different lifetimes. When the lifetimes of the component multiplets are different, these lifetimes often can be separated by decomposition of the data into its straight-line components (see below). A special case of the separation of the lifetimes of the fine-structure levels of hydrogen ($n=3$ and $n=4$) by decomposition of the curve of decay is illustrated by the work of Goodman and Donahue.[6]

The analysis of the present data for the cascade-free multiplets presented in Table I can be illustrated by considering the ion N II. Several multiplets of N II appear to be free from cascading. The lifetime of one of these cascade-free multiplets, N II 1085, was measured recently by Lawrence and Savage[13] using a phase-shift method. This measurement is apparently the only experimental check on the present data. All multiplets of N II measured here were transitions to the ground term $2s^22p^2\,{}^3P$. They are identified in the term diagram of Fig. 3. One group of multiplets (1085, 916, and 645 Å) has the configuration $2s2p^3$ for the upper terms. Although these terms can be populated by cascade transitions from the two higher terms $2p^4\,{}^3P$ and $2s2p^23s\,{}^3P$, the data indicate that cascading is negligible. Lawrence and Savage[13] also did not observe cascading for the multiplet N II 1085. An estimate of the cascading lifetime from the common upper term $2p^4\,{}^3P$ into the three terms of the configuration $2s2p^3$ can be obtained from theoretical calculations by Kelly.[14] The calculated lifetime of the $2p^4\,{}^3P$ term, which will also be the characteristic lifetime for the cascading transitions, is 1.6×10^{-10} sec. This lifetime will be identical for the cascading transitions into the three different terms of the configuration $2s2p^3$, but the transition ${}^3D^0$–${}^3P$ will be most intense because of its higher transition probability. Cascading with this characteristic lifetime should be readily apparent in the data on I versus l for the multiplets originating from the term configuration $2s2p^3$. Since it is not observed with any significant magnitude, it appears that the term $2p^4\,{}^3P$ for N II is not populated to any extent by the interaction of the ion beam and foil. A similar analysis indicates that cascading from the $2s2p^23s\,{}^3P$ term into the three terms having the configuration $2s2p^3$ also is not important.

Figure 4 illustrates typical data obtained for the three cascade-free multiplets of N II where the counts as a function of foil position l are plotted for the multiplet N II 916. The data have been corrected for background noise only. Because of the low counting rates, the data for each position of the foil were accumulated for counting intervals of 100 sec. This time interval was used for all measurements of lifetime presented here. The rapid decrease in signal with decreasing l observed near the intersection of the foil and beam is due to the foil's entering the field of view of the monochromator (see Fig. 1). For large values of foil position, the observed counting rate of the multiplet approaches a constant value of background noise. For large l, both the uncorrected signal and the background are large numbers. Their difference represents the corrected signal which is a small number. Therefore, the scattering of the

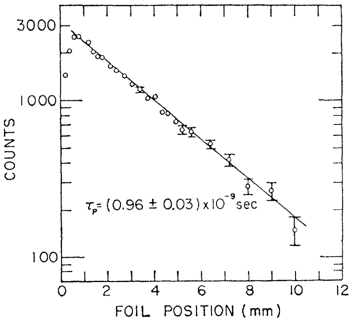

FIG. 4. Counts versus foil position for the multiplet N II 916.3. The counting interval for each point was 100 sec. The beam energy was 1 MeV and the foil thickness 500 Å.

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[13] G. M. Lawrence and B. D. Savage, Phys. Rev. **141**, 67 (1966).

[14] P. S. Kelly, Astrophys. J. **140**, 1247 (1964).

data, in general, increases with increasing foil position. The lifetime of the term $2s2p^3\,{}^3P^0$ given in Fig. 4 was obtained from the slope of the straight line fitted to the experimental data. The indicated error in lifetime was obtained graphically from the range of straight lines that fell within the indicated standard deviation of the experimental data.

The data for the multiplet N II 645 originating from the upper term $2s2p^3\,{}^3S^0$ do show two distinct lifetimes of 0.11 and 1.7×10^{-9} sec. The shorter lifetime, 0.11×10^{-9} sec, was assumed to be the lifetime of the $2s2p^3\,{}^3S^0$ term since it is close to the theoretical value listed by Wiese *et al.*[15] The longer lifetime almost certainly originates from a very strong broad emission line near 323 Å (multiplets of N III and N IV) which would also be present in second order near 646 Å. A cascade transition into the $2s2p^3\,{}^3S^0$ term from either the $2p^4\,{}^3P$ or $2s2p^23s\,{}^3P$ term was ruled out because the stronger transitions into the two other terms having the configuration $2s2p^3$ were not observed (see discussion above). The accuracy of the lifetime measurement is, of course, reduced because of blending, and the errors assigned to the data of Table I take this blending into account.

In addition to the three multiplets of N II, one other multiplet, N III 991, appears to be free from cascading. The remaining multiplets listed in Table I exhibit cascading to some extent, and corrections for cascading were applied to obtain the values of lifetime listed. The data indicate that for many of these multiplets, cascading is small in magnitude with a cascading lifetime widely separated from the lifetime of the upper term of the multiplet. These multiplets are identified in the table as exhibiting weak cascading. Cascading may be an important process for some of these multiplets, but appears to be weak in the data on I versus l because the cascading lifetime is outside of the range of measurements possible in this experiment. Cascading processes having a very short lifetime will be most important for small foil positions, and, because of the difficulty in establishing $l=0$ (see Figs. 1 and 4), these short-lifetime cascade processes may not be apparent. Also, cascading transitions with long lifetimes will be strongly discriminated against because of the parameter $\Delta l/v\tau_c$, previously discussed. The procedure used here to correct for cascading in general is illustrated below for the multiplet N V 209. This multiplet is one of several multiplets which exhibit strong cascading (see Table I).

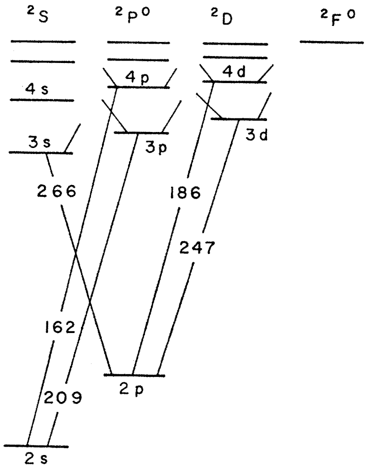

FIG. 5. Partial-term diagram of N V.

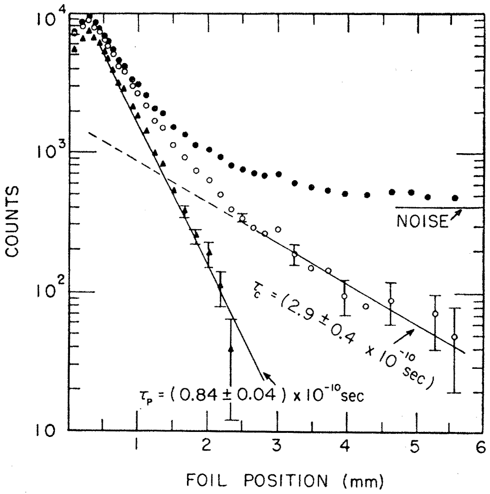

FIG. 6. Counts versus foil position for the multiplet N V 209.3. The data were obtained with a foil thickness of 500 Å, a beam energy of 2 MeV, and a counting interval of 100 sec; ●, uncorrected data; ○, data corrected for background noise; ▲, data corrected for both noise and cascading.

The term diagram of N V, given in Fig. 5, identifies the multiplets observed here. Because of severe blending of the multiplet N V 247 with the strong resonance multiplet of N IV, the lifetime of the $3d\,{}^2D$ term could not be measured. All of the excited terms of N V can be partially populated by cascade transitions. The data indicate particularly strong cascading for the multiplets N V 209 and N V 186. The procedure used to correct for cascading is indicated in Fig. 6, where counts versus foil position are plotted for the multiplet N V 209. The data were obtained with a 2 MeV N^+ beam, a 10 μg cm^{-2} (500-Å thick) carbon foil, and a counting interval of 100 sec. The solid points are the uncorrected experimental data which converge to a background level of 4.2 counts sec^{-1} for large foil positions. After subtracting the background from the uncorrected data, the middle curve (open circles) is obtained which represents the spatial decay of the multiplet, I versus l. The standard deviation of the corrected data, which increases progressively with increasing foil position above about 3 mm, is indicated in the figure for a few foil positions. The corrected data are seen to reduce to a curve characterized by a rapid decrease in counts with increasing foil position between about 0.25 and 2 mm,

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[15] W. L. Wiese, M. W. Smith, and B. M. Glennon, *Atomic Transition Probabilities* (U. S. Government Printing Office, Washington, D. C., 1966), Vol. 1.

followed by a slower decrease for foil position greater than about 2.5 mm. The slow decay was assumed to originate from strong cascade transitions into the $3p\,^2P^0$ term. The lifetime associated with this cascading, τ_c, was obtained from the slope of the straight line fitted to this limiting slow decay, The error assigned to τ_c ($\pm 15\%$) is due to the uncertainty in fitting a straight line to the corrected data. By extending the straight line, τ_c, toward $l=0$, counts originating from cascading can be established. When this contribution is subtracted from the noise-corrected data, a distribution of points (triangles) about a straight line is obtained. The slope of this line yields a mean lifetime, τ_p, of 0.84×10^{-10} sec, which is assumed to be the lifetime of the upper term $3p\,^2P^0$ of the multiplet N v 209. The error assigned to τ_p takes into account the large estimated error in the cascade transition. For this particular multiplet, an error of about $\pm 15\%$ in the determination of the cascading transition τ_c introduces an error of about $\pm 5\%$ in the determination of τ_p.

The origin of the cascading lifetime τ_c for the multiplet N v 209 is difficult to identify, since it may be a superposition of several cascades from higher excited terms into the $3p$ term. This strong cascading apparently originates from terms above the two adjacent terms $4s$ and $4d$, since τ_c is significantly longer than the lifetime of the $4s$ and $4d$ terms. Higher terms of N v are known to be excited using a beam energy and carbon foil similar to those used here.[1] Some cascading from the terms $4s$ and $4d$ into the $3p$ term also will be present. However, the data of Fig. 6 indicate that this cascading is not too important. An estimate of the magnitude of the cascading from the important transition $3p$–$4d$, which has a cascade lifetime of 0.65×10^{-10} sec (see Table I), can be obtained from Eq. (2) assuming that the photometric efficiency of the monochromator is the same at 186 and 209 Å and knowing that the lifetimes of the $3p$ and $4d$ terms are nearly the same. From the ratio of the observed counting rates for the multiplets N v 186 and 209 in Fig. 2, the relative initial population of the $4d$ and $3p$ terms, $N_{4d}{}^0/N_{3p}{}^0$, is seen to be approximately 0.3. Since the calculated branching fraction for the transition $3p$–$4d$ is 0.23, cascading from the $4d$ term into the $3p$ term should contribute about 8% to the population of the $3p$ term. The magnitude of the cascading transition, therefore, is small, and its effect on the slope of the data on I versus l of Fig. 6 should also be small.

The data for the multiplet N v 186 are similar to N v 209 in that strong cascading with a long characteristic lifetime is apparent for I versus l. The lifetime measurement in Table I for this multiplet was obtained by correcting for this long-cascade lifetime. Cascading was nearly negligible for the strong multiplet N v 266, and apparently negligible for the multiplet N v 162, although this was difficult to establish with certainty for the latter multiplet because of its low counting rate (see Fig. 2). The data in Table I for the two multiplets N v 266 and 162 were obtained by fitting a single exponential to the noise-corrected data I versus l.

V. RESULTS

The measurements of lifetimes are summarized in Table I. When L–S coupling is assumed, the experimental data give the lifetime τ_p and the total Einstein transition probability A_p ($=1/\tau_p$) of the upper term of the multiplet. The data in columns 4 and 5 are thus direct experimental measurements for the upper terms of the multiplets listed in column 3. The transition probability A_{pk} for the multiplet, in column 6, is given by the product of A_p and the fraction of the total transitions from term p which go to the lower term k. When the measured multiplet is the only transition from term p, the branching fraction is unity and A_{pk} is identical to A_p. The two multiplets N IV 335 and N v 209 do not strictly fall into this category. However, for these two multiplets, the A_{pk}'s are essentially identical to the experimental A_p's since the calculated branching fractions for N IV 335 and N v 209 are, respectively, 0.995 and 0.997. Several multiplets listed in Table I have branching fractions significantly different from unity. The values of A_{pk}, given in column 6, for three of these multiplets (N II 529, N v 162, and N v 186) were obtained using calculated branching fractions. The uncertainty in the branching fraction is probably less than 20% for the two multiplets N v 162 and 186, but may be greater than 50% for the multiplet N II 529. The experimental data for N IV 345 and 351 were not corrected, since the uncertainty in the branching fraction is large.

Values of A_{pk} from other sources are listed in the last column of Table I for comparison. The only experimental value is for the resonance multiplet N II 1085, measured by Lawrence and Savage.[13] Within their quoted limits of experimental error, this value agrees with the present measurement.

The remaining values of A_{pk} in column 7 are theoretical values. With the exception of a few values obtained from tables by Griem,[16] who used the Coulomb approximation of Bates and Damgaard[17] to calculate the oscillator strengths of the multiplet, the theoretical calculations are the "best" values selected by Wiese *et al.*[15] For most of the multiplets of N II, III, and IV listed in Table I, Wiese *et al.* assigned an uncertainty in the theoretical values of 50% or greater. The one exception is for the multiplet N IV 335, where an error of 25% is expected for the theoretical calculation. The agreement between the present experimental value and the theoretical value for this multiplet is seen to be particularly good. Configuration interaction is expected to be important for these uv multiplets in N II through N IV. Configuration interaction was considered as a

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[16] H. R. Griem, *Plasma Spectroscopy* (McGraw-Hill Book Company, Inc., New York, 1964), p. 428.

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

first approximation by Bolotin *et al.*[18] for the three multiplets of N II 1085, 916, and 645 and taken into account only crudely by Bolotin and Yutsis[19] for the two multiplets N III 991 and 685. For the remaining multiplets of N II through N IV, configuration interaction was neglected in the theoretical calculation.

The agreement between the theoretical and experimental values for the four multiplets of N V is in general good. The theoretical values for the multiplets N V 209 and 266 are from the Hartree-Fock calculations of Weiss[20] who used the dipole-length and dipole-velocity forms of the oscillator strengths. Both the length and velocity values are listed in the table, although the length value should be more reliable (5–10%). Calculations by Griem[16] for these two transitions, obtained from the Coulomb approximation, also give results which are nearly identical to the dipole-length values. The theoretical values for the multiplets N V 162 and N V 186 are from the tables by Griem.[16] These values should be reasonably accurate (perhaps to 20%), since the ion is light and the atomic system simple. In addition, for the N V 186 multiplet, the transition is between excited levels. Cascading was particularly severe for the multiplets N V 209 (see Fig. 6) and N V 186, and less important for the multiplets N V 266 and 162 (see previous discussion). The values of A_{pk} for N V 162 and 186 listed in column 6 are subject to additional errors introduced by the calculation of the branching fractions.

Several intense uv multiplets are not listed in Table I because of blending. These include the two unresolved multiplets N III 763.8 and N IV 765.1, both transitions to the ground-term configuration. Similarly, the resonance-series multiplet N IV 247.2 and the multiplet N V 247.6 were unresolved. The weak multiplet N III 533.7, indicated in Fig. 3, also is omitted from Table I because of blending with the multiplet N V 266.2 in second order. Two multiplets listed in the table, N II 645 and N II 671, were blended with other multiplets. The lifetime of these multiplets, however, could be separated from the interfering multiplets. The multiplet N II 645 was discussed previously in Sec. IV. The multiplet N II 671.5 was blended with N IV 335.1 which was strong in second order. The lifetime of this interfering multiplet could be identified, since it was also measured in first order (see Table I).

The errors estimated in Table I vary with the particular multiplet and were introduced from several sources. The chief source of error results from corrections for cascade transitions into the upper term of the multiplet. This error increases as the lifetime of the cascade transition approaches the lifetime of the upper term of the multiplet. Similar errors arise when blending of two or more multiplets occur. When cascading is negligible, the errors arise predominantly in fitting the data to an exponential. These errors depend both on the ratio of signal-to-background of the multiplet and on the short-term fluctuations in the ion-beam current of about ±5%. These short-term fluctuations are generally not too important since, for all measurements of lifetimes, the data were averaged over much longer counting intervals (100 sec). Data of Northcliff[21] were used to calculate the energy loss by the beam in the foil. For the foils and ion energies used, $\Delta E/E$ was between 4 and 7%. The errors introduced into the determination of the velocity due to errors in $\Delta E/E$ and due to errors in the determination of the energy of the incident ion beam from the accelerator are between 1 and 2%. Scattering of the ion beam by the foil should be negligible, because the foil translation distances were small.

ACKNOWLEDGMENTS

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[18] A. B. Bolotin, I. B. Levinson, and L. I. Levin, Zh. Eksperim. i Teor. Fiz. **29**, 449 (1955) [English transl.: Soviet Phys.—JETP **2**, 391 (1956)].

[19] A. B. Bolotin and A. P. Yutsis, Zh. Eksperim. i Teor. Fiz. **24**, 537 (1953).

[20] A. W. Weiss, Astrophys. J. **138**, 1262 (1963).

[21] L. C. Northcliff, Ann. Rev. Nucl. Sci. **13**, 89 (1963).