Radiative-lifetime measurements for F II using a doubly differentially pumped gas target

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Studies have been conducted using the ion-beam–gas excitation method with a doubly differentially pumped gas target (with a pressure ratio of 10^4 to 1 or more between gas target and observation chamber) to obtain the first known radiative-lifetime measurements for the $3p\ ^5P$ (3849 Å), $3p\ ^3P$ (4025 Å), $3d\ ^5D^0$ (3504 Å), $3p'\ ^3D$ (4114 Å), $3p'\ ^1F$ (4299 Å), and $3p'\ ^3F$ (3901 Å) levels of F II. The lifetimes of these levels were measured as 8.17 ± 0.29, 8.18 ± 0.24, 5.74 ± 0.20, 10.62 ± 0.08, 10.41 ± 0.68, and 9.45 ± 0.34 ns, respectively. In addition, the lifetime associated with 3602-Å F II transition was measured as 4.40 ± 0.27 ns, the level (*s*) of origin being undetermined (either $3p''\ ^3P$ or $3d'\ ^3G^0$). The uncertainties given are two times the standard deviations of the means (~95% confidence level). Absolute uncertainties are estimated to be less than 10%.

I. INTRODUCTION

The ion-beam–foil excitation method[1] and the closely related ion-beam–gas excitation method[2-4] have been among the most prolific sources of accurate radiative-lifetime measurements in recent years. The results from these two methods do not usually overlap as the ion-beam–foil excitation method generally produces highly ionized excited states while the ion-beam–gas excitation method is especially suited to the study of doubly and singly ionized atoms and molecules as well as excited neutrals. Together, these two methods have been used to obtain lifetimes for a large number of atomic transitions.

In this paper we present the lifetimes of various levels of F II obtained by the ion-beam–gas excitation method.[5] The levels and the corresponding wavelengths of the transitions (in parentheses) used to measure the lifetimes of these levels were $3p\,^5P$ (3849 Å), $3p\,^3P$ (4025 Å), $3d\,^5D^0$ (3504 Å), $3p'\,^3D$ (4114 Å), $3p'\,^1F$ (4299 Å), $3p'\,^3F$ (3901 Å), and $3p''\,^3P$ or $3d'\,^3G^0$ (3602 Å). These levels and transitions are shown in the term diagrams of F II, Figs. 1–3. The transitions with arrowheads are those reported in this paper.

II. APPARATUS AND EXPERIMENTAL TECHNIQUE

The basic apparatus and experimental procedure used in our measurements have been described elsewhere in detail.[2-4] Briefly, hydrogen-fluoride gas was used to obtain an HF^+ beam (22–28 keV) which was dissociated and excited by passing it through a doubly differentially pumped gas target (DDPGT) shown in Fig. 4. The emitted radiation was detected by a Jarrel-Ash 82-000 $\frac{1}{2}$-m grating monochromator with a cooled EMI 9558QB photomultiplier tube (PMT). Signals were recorded using standard pulse-counting instrumentation. Decay curves were obtained by translating the monochromator downstream from the exit of the DDPGT. Measurements of intensity I were obtained as a function of distance x downstream. A second ($\frac{1}{4}$-m) monochromator/PMT combination measured the intensity at a fixed point for purposes of normalizing the output of the first detection system.

A computer program was used to fit the intensity data to a sum of exponentials and a constant of the form $I = A\,e^{-x/v\tau_k} + \sum_j B_j\,e^{-x/v\tau_j} + C$, where A and B_j are constants, v is the speed of the ions, τ_j and τ_k are the lifetimes of levels j and k, and C is a constant which accounts for intensity from residual-gas excitation.

The use of the DDPGT allowed the pressure of the target gas (helium) to be held fixed at 125 μ while the observation-chamber pressure was maintained at $\leq 10^{-5}$ Torr. A high-resolution spectral scan taken at the exit aperture of the DDPGT (with an incident ion beam of HF^+) showed no spectral lines of helium, indicating that gas streaming from the target was minimal.

III. DATA ANALYSIS AND RESULTS

A spectrum of the excited ion species resulting from HF^+ (taken within 2 mm downstream from the entrance to the observation chamber) is shown in Fig. 5. High-resolution scans were made of the principal lines shown to ensure that there were no close-lying spectral lines which could interfere with the spectral line of interest.

All of the lifetime data for singly ionized atomic fluorine were obtained using beams of HF^+. High-resolution spectral scans of the resulting ionic species showed the presence of excited F^+ and H atoms. No spectral lines of F I or F III appeared in the spectrum. All intensities were very weak.

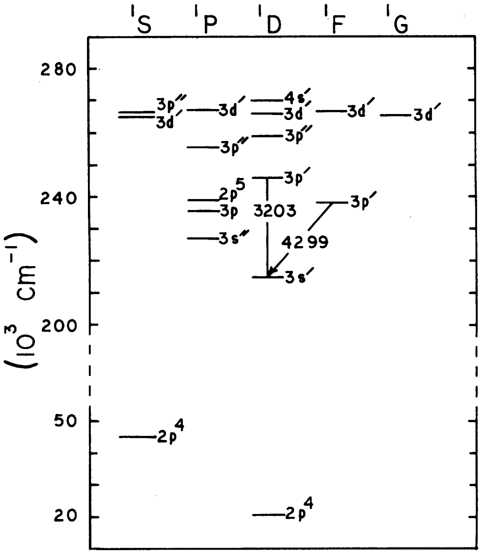

FIG. 1. Singlet-term diagram of F II. The transition indicated by the arrow was used to measure the $3p'\,^1F$ lifetime.

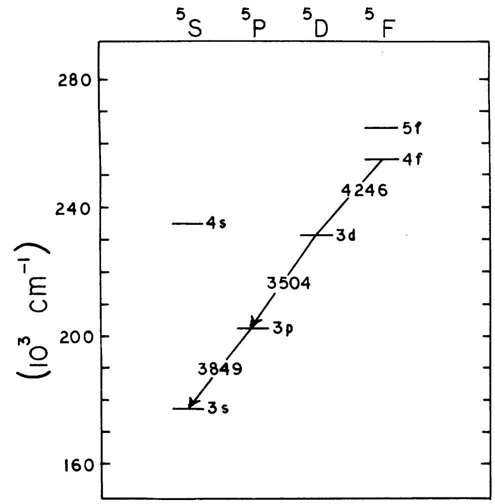

FIG. 3. Quintet-term diagram of F II.

A. $3p\,^5P$

The lifetime of the $3p\,^5P$ level of F II was obtained from the decay curve of the $3p\,^5P$-$3s\,^5S^0$ ($\bar{\lambda}=3849$ Å) transition. This was the strongest line in the spectrum and was well separated from adjacent lines; consequently, monochromator slits were opened to 2.0 mm to increase the signal intensity. (Reciprocal linear dispersion was 16 Å/mm.) Figure 6 shows a typical decay curve for this transition. This experimentally obtained curve (X's) was fitted to the sum of two exponentials and a constant and gave a value of 8.41 ± 0.26 ns. Four additional decay curves were taken for this transition, and all five were fitted to two exponentials and a constant. They yielded a weighted average lifetime of 8.17 ± 0.29 ns. The quoted uncertainty is two times the standard deviation of the mean.

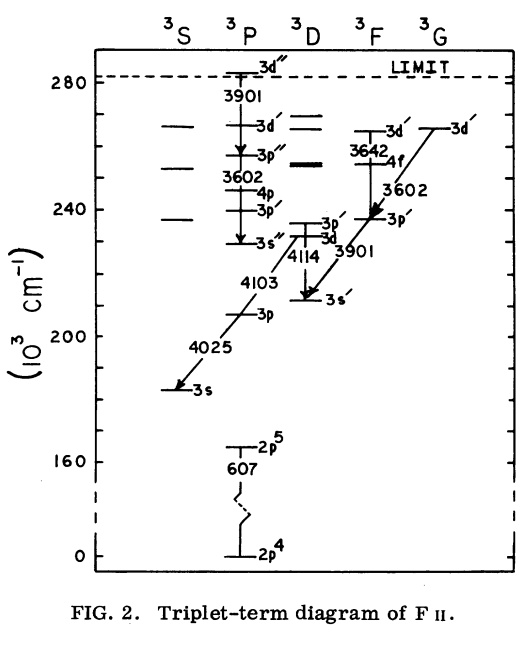

FIG. 2. Triplet-term diagram of F II.

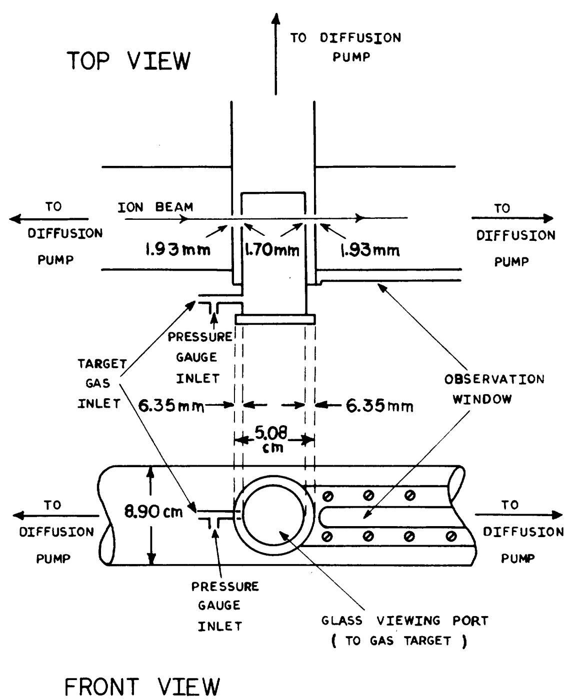

FIG. 4. Top and front view of the doubly differentially pumped gas target (DDPGT) and a portion of the observation chamber.

B. $3p\,^3P$

The lifetime of the $3p\,^3P$ level of F II was obtained from the decay curve of the $3p\,^3P$-$3s\,^3S^0$ ($\bar{\lambda}=4025$ Å) transition. This line was well separated from adjacent lines, allowing a slit width of 2.0 mm to be used for intensity measurements. The decay curves were all fitted to the sum of two exponentials and a constant, yielding a weighted average lifetime of 8.18 ± 0.24 ns for the four measurements made.

C. $3d\,^5D^0$

The decay of the $3d\,^5D^0$-$3p\,^5P$ ($\bar{\lambda}=3504$ Å) transition was used to measure the lifetime of the $3d\,^5D^0$ level of F II. This line was also well separated from adjacent lines, allowing a slit width of 2.0 mm to be used on the monochromator. The intensity of this line was very low and required long counting times (several minutes per point) to acquire adequate data. Three decay curves were taken, giving a weighted average lifetime of 5.74 ±0.20 ns. These decay curves were fitted to the sum of two exponentials and a constant.

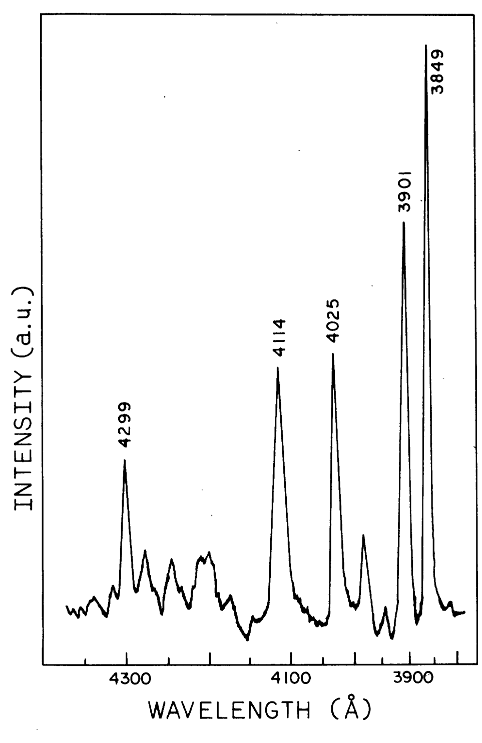

FIG. 5. Partial spectrum of an excited HF^+ beam taken within the first 2 mm of the upstream end of the observation chamber. Intensity is in arbitrary units (a.u.).

D. $3p'\,^3D$

The $3p'\,^3D$-$3s'\,^3D^0$ ($\bar{\lambda}=4114$ Å) transition was used to measure the lifetime of the $3p'\,^3D$ level of F II. A typical decay curve for this transition is shown in Fig. 7, the computed lifetime being 10.26 ± 0.12 ns. This transition results in a multiplet of lines very close to an adjacent multiplet ($\bar{\lambda}=4103$ Å) from the $3d\,^3D^0$-$3p\,^3P$ transition of F II.

In our high-resolution spectral scans made at the downstream exit from the DDPGT no 4103-Å spectral line was observed. As a precautionary measure to prevent any significant blending should the 4103-Å line be present, the slit widths on the monochromator were set at 0.8 mm (corresponding to a spectral window of 13 Å). If the 4103-Å line were present, the very low intensity from this line together with the spectral-window setting should make any contributions from the 4103-Å line minimal. The four decay curves taken were all fitted to one exponential and a constant, giving a weighted average value of 10.62 ± 0.08 ns.

E. $3p'\,^1F$

The lifetime of the $3p'\,^1F$ level was obtained from the $3p'\,^1F$-$3s'\,^1D^0$ ($\bar{\lambda}=4299$ Å) transition of F II. This was the only transition observed from a singlet term. The spectral separation from adjacent lines was adequate to allow use of 2.0-mm slit widths on the monochromator. The four decay

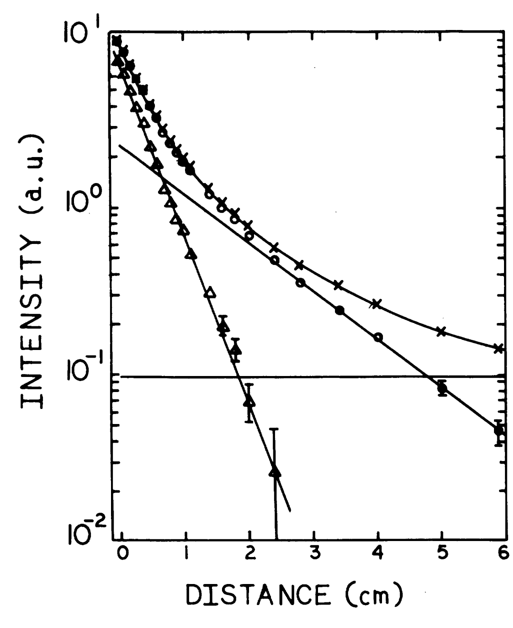

FIG. 6. Typical decay curve of the $\bar{\lambda}=3849$-Å transition of F II. Intensity is in arbitrary units (a.u.) and is normalized to 10 at $x=0$. Beam energy was 25.2 keV. The lifetime for this decay curve was 8.41 ± 0.26 ns.

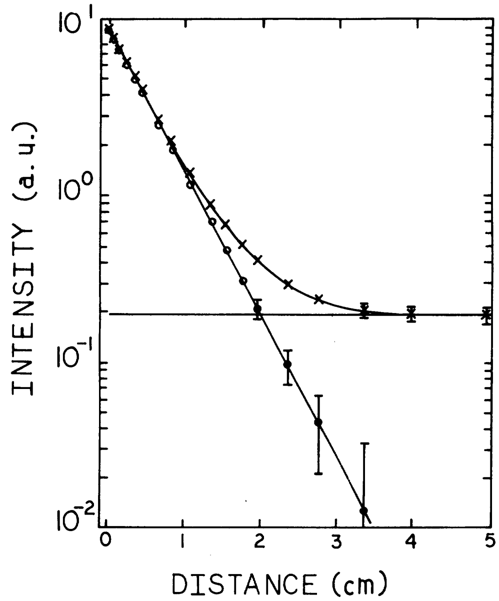

FIG. 7. Typical decay curve of the $\bar{\lambda}$=4114-Å transition of F II. Intensity is in arbitrary units (a.u.). Beam energy was 25.2 keV. The lifetime for this decay curve was 10.26 ± 0.12 ns.

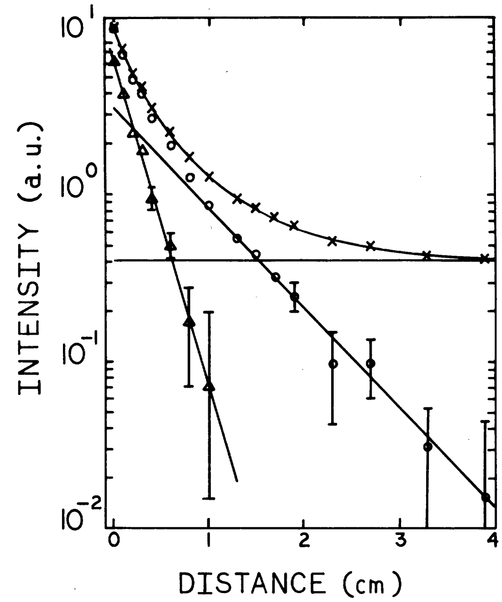

FIG. 8. Typical decay curve of the $\bar{\lambda}$=3602-Å transition of F II. Intensity is in arbitrary units (a.u.). Beam energy was 26.0 keV. The lifetime for this decay curve was 4.45 ± 0.76 ns.

curves taken from this transition gave a weighted average value of 10.41 ± 0.78 ns. They were all fitted to the sum of two exponentials and a constant.

F. $3p'\,^3F$

In analyzing the spectrum of F II two spectral lines ($\bar{\lambda}$ = 3901 Å and $\bar{\lambda}$ = 3602 Å) resulting from transitions not listed by Wiese, Smith, and Glennon[6] were observed. A computer program written by T. N. Lawrence[7] was used to generate all allowed transitions for F II in an attempt to identify these transitions. The energy levels put into the program were obtained from Moore.[8] Our analysis indicates that the 3901-Å line may arise from either the $3p'\,^3F$-$3s'\,^3D^0$ or the $3d''\,^3P^0$-$3p''\,^3P$ transition. Palenius[9] also identified lines of approximately this wavelength with the transitions $3p'\,^3F$-$3s'\,^3D^0$ and $3d''\,^3P^0$-$3p''\,^3P$.

The resolution required to separate these transitions is beyond the capability of our apparatus. Even if such resolution were attainable, the intensity would be too weak to make lifetime measurements. However, the upper level of the latter transition lies beyond the F III limit of F II, and since no previous transitions of levels that high have been observed in our laboratory, it is concluded that the transition responsible for our 3901-Å line was probably $3p'\,^3F$-$3s'\,^3D^0$.

As previously noted (Sec. II), high-resolution spectral scans taken at the downstream exit from the DDPGT showed no spectral lines of helium. As a precautionary measure to prevent any significant blending should the 3888-Å line of He I be present (the 3888-Å line did not appear in our high-resolution scans), the slit widths on the monochromator were set at 0.8 mm. Three decay curves were taken for this transition, yielding a weighted average value of 9.45 ± 0.34 ns for the lifetime of the $3p'\,^3F$ level of F II. All three curves were fitted to the sum of two exponentials and a constant.

G. $3p''\,^3P$ (or $3d'\,^3G^0$?)

The other observed transition(s) of undetermined origin occurred at a wavelength of 3602 Å. Palenius[9] has observed lines at approximately this wavelength from transitions $3d'\,^3G^0$-$3p'\,^3F$ and $3p''\,^3P$-$3s''\,^3P^0$. Again, the resolution required to separate these transitions is beyond the capability of our apparatus. The three decay curves of the 3602-Å transition were fitted to the sum of two exponentials and a constant giving a weighted average value of 4.40 ± 0.27 ns. A typical decay curve appears in Fig. 8. The two exponential components in the decay curves may arise from a blend of both transitions mentioned above. Thus, at this time no definite transition is assigned to the lifetime quoted above.

TABLE I. Lifetimes of various levels of F II.

Levels	Multiplet [a] no.	λ(Å) [b]	This work (ns) [c]	Theory (ns)
$3p\ ^5P$	(1)	3849	8.17 ± 0.29	7.7 (50%) [d] 9.3 [e]
$3p\ ^3P$	(2)	4025	8.18 ± 0.24	8.3 (50%) [d]
$3d\ ^5D^0$	(3)	3504	5.74 ± 0.20	3.5 (25%) [d]
$3p'\ ^3D$	(5)	4114	10.62 ± 0.08	5.6 (50%) [d]
$3p'\ ^1F$	(7)	4299	10.41 ± 0.68	5.9 (50%) [d]
$3p'\ ^3F$	(–)	3901	9.45 ± 0.34	
$3p''\ ^3P$ or $3d'\ ^3G^0$(?)	(–)	3602	4.40 ± 0.27	

[a] Reference 10.

[b] These are the wavelength settings on our monochromator and correspond to the average wavelength of the multiplet.

[c] Error quoted is two times the standard deviation of the mean. This gives a better than 95% confidence level. Absolute uncertainty is estimated to be less than 10%.

[d] Coulomb approximation from Wiese, Smith, and Glennon, Ref. 6. The numbers in parentheses are the maximum estimated uncertainties in the theoretical values.

[e] Calculated using interpolated oscillator strengths from Smith and Wiese, Ref. 11.

IV. DISCUSSION

Our results are summarized in Table I. The errors quoted are two times the standard deviations of the mean. All decay curves taken (except for the 4114-Å line) were fitted to the sum of two exponentials and a constant, indicating the presence of cascade. Where appropriate, transitions are labeled by the multiplet numbers assigned in the tabulation by Moore.[10]

The results of the only theoretical calculations known to us are also given in Table I.[6,11] We are unaware of any other experimental results.

The most important systematic error in this work was possibly unresolved cascading. Allowing for a 2% uncertainty in velocity determination, we estimate the maximum uncertainty in our measured F II lifetimes to be less than 10%.

ACKNOWLEDGMENTS

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[1] W. S. Bickel, Appl. Opt. 7, 2367 (1968). The reader is also referred to recent review articles in Nucl. Instrum. Methods 110, 35 (1973); 110, 11 (1973); 110, 79 (1973); 110, 445 (1973); 110, 343 (1973); 110, 333 (1973); 110, 1 (1973); 110, 477 (1973); and 110, 193 (1973).

[2] S. A. Chin-Bing, C. E. Head, and A. E. Green, Jr., Am. J. Phys. 38, 352 (1970).

[3] C. E. Head and M. E. M. Head, Phys. Rev. A 2, 2244 (1970).

[4] J. H. Clark and C. E. Head, Phys. Rev. A 6, 1722 (1972).

[5] Preliminary results for some F II levels had been previously reported, see S. A. Chin-Bing and C. E. Head, Bull. Amer. Phys. Soc. 16, 1344 (1971).

[6] W. L. Wiese, M. W. Smith, and B. M. Glennon, *Atomic Transition Probabilities*, Natl. Bur. Std. Circ. No. 4 (U. S. GPO, Washington, D. C., 1966).

[7] T. N. Lawrence, ENGLEV.F4 (Physics Department, Louisiana State University, New Orleans, 1973) (unpublished).

[8] C. E. Moore, *Atomic Energy Levels*, Natl. Bur. Std. Circ. No. 467 (U. S. GPO, Washington, D. C., 1949), Vol. I.

[9] H. P. Palenius, Ark. Fysik. 39, 15 (1969).

[10] C. E. Moore, *A Multiplet Table of Astrophysical Interest, Revised Edition*, Natl. Bur. Std. Tech. Note 36 (U. S. GPO, Washington, D. C., 1959).

[11] M. W. Smith and W. L. Wiese, Astrophys. J. Suppl. Ser. 23, 103 (1971).