Beam-Foil Spectroscopy of Sodium between 0.5 and 2 MeV

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The optical excitation of a beam of Na^+ ions by a thin carbon foil has been observed in the spectral range 1100–6000 Å. Ions with a charge state as high as 5^+ were present in the beam after the foil. A large number of untabulated lines has been detected and several identifications are proposed mainly in the Na IV and Na V spectra. The decay along the beam of numerous transitions in Na II and Na III has also been recorded. In a few favorable cases, the resolution of the decay curve gives a useful estimate of the mean life of the corresponding excited state.

I. INTRODUCTION

Before anything more physical can be done with a new light source, one has first to investigate its properties: emission characteristics, excitation processes, perturbating influences, etc. Most of the recently published literature on the beam-foil source is devoted to such technological aspects and the present paper is no exception.

There are, however, some good reasons to devote a large degree of attention to the new features of that source. The excitation mechanism in the foil is not understood in any detail and represents an interesting problem in the field of atomic collisions in solids. The perturbing influence of magnetic fields has just been looked into[1] and will lead hopefully to a broad field of physical applications. Finally, the surprising emission characteristics remain as a permanent challenge for the atomic spectroscopist.

From that point of view the sodium spectrum looked like a very useful example. A first survey of the spectrum by Brown *et al.*[2] revealed 72 unidentified lines in the visible range. Preliminary investigations[3] carried out in the ultraviolet have shown that the line density is also high in that domain.

Our first purpose in that paper was to identify the emitters and to tentatively classify the transitions emitted when a beam of Na^+ ions is excited by a thin carbon foil in the spectral range 1200–6000 Å. The Na II and Na III spectra have already been thoroughly investigated by classical means. Past experience with beam-foil experiments indicates, however, that this new mode of excitation can produce interesting changes even in such apparently well-established classifications. With respect to the higher charge states (Na IV and Na V) no record exists in the literature of earlier observations in the studied spectral range.

Although beam-foil is plagued with severe drawbacks to be considered later, it has one big advantage: It allows the observation of the decay of the light emitted after an excitation well localized in time and/or space. Consequently, the first application of beam-foil has been to the measurement of mean lives of atomic excited states. In the case of sodium, Andersen *et al.*[4,5] reported recently about their measurements of the $3p$ levels of Na II and several $3p$ and $3d$ levels in Na III. A critical discussion of this kind of measurement has, however, been initiated by Wiese[6] and there is strong suspicion that the influence of cascade phenomena, especially in the case of sodium, had been underestimated. The fundamental interest of such quantities as atomic lifetimes and related transition probabilities seemed to justify further measurements in Na II and Na III with special care given to cascades in the light of the preceding remarks.

II. EXPERIMENT

The beam of Na^+ ions was provided by a 2-MeV vertical Van de Graaff accelerator. The adapted ion source was developed in our laboratory by Buchet[7] following an older design by Blewet and Jones.[8] It uses the highly efficient thermoionic emission of a pearl of sodium aluminum silicate heated in a vacuum by a tungsten filament. This type of source possesses some interesting features, like high stability, high purity, low-energy dispersion, and low-power requirement. Currents as high as 50 μA of singly charged sodium can be obtained after magnetic analysis.

In the energy range 500–800 keV, we were able to bend the beam at 90°, but beyond that point the available magnet reached saturation. We were then forced to use the direct vertical beam. Except for minor mechanical difficulties our measurements were not altered, due to the good quality of the source. The spectroscopic analysis of the light emitted after a target at 800 keV with and without magnetic analysis did not reveal any significant difference between the two cases.

The targets were self-supporting carbon foils,

1 cm in diam with densities ranging from 5 $\mu g/cm^2$ up to 20 $\mu g/cm^2$. Their average lifetime in a broad beam of a few microamperes was of the order of 15 min at 800 keV. The pressure in the target chamber was kept lower than 10^{-5} Torr in order to minimize the influence of collisions with the residual gas.

For the analysis of the emitted light, we used a Czerny-Turner 0.75-m Spex spectrometer with an EMI 6256 S phototube or a 0.3-m McPherson model 218 vacuum spectrometer with the EMR Ascop 541 FO 8 photomultiplier.

In the vacuum ultraviolet the entrance slit of the spectrometer was set directly at a short distance (15 cm) and perpendicular to the beam axis. The foil could be moved in the vacuum along the beam. As clearly indicated in Fig. 1(b), it is the light emitted by a rather long portion of the beam (2 cm) which is observed in that case. Such a setting is not suitable for the measurement of short mean lives.

In the visible and quartz ultraviolet, we used different light collecting devices. Best resolutions

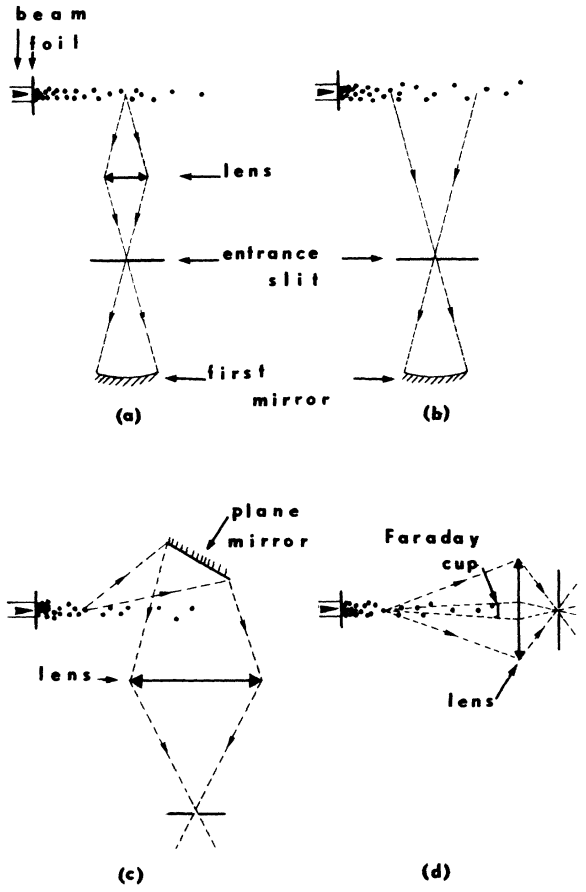

FIG. 1. Experimental settings (not to scale). (a) and (b): "side-on" systems; (c) and (d): "end-on" mirror and lens systems.

were obtained with "end-on" systems (setting c and d on Fig. 1) which reduce the influence of Doppler broadening. For mean-life measurement purposes, we used a "side-on" system with a quartz lens focusing onto the entrance slit of the spectrometer the photons emitted in a rather large solid angle by a length of the beam of a few hundred microns. The spectrometer could be moved in front of a quartz window in a direction accurately parallel to the beam axis (setting a on Fig. 1).

In all cases, the photomultiplier current was detected and dc amplified. The resulting signal and the beam current collected on a Faraday cup were simultaneously recorded on a strip-chart recorder.

III. SPECTRAL ANALYSIS

Summarizing the results obtained at various energies between 500 keV and 1.8 MeV, one may state that 300 lines are emitted by the excited sodium ions in the spectral range 1100–6000 Å. The identification of the charge state of the emitters is complicated by the fact that there is no information available in the literature concerning the equilibrium charge distribution in a Na^+ beam after passage through a carbon target. Whenever necessary we relied on calculations based on the semiempirical method of Dmitriev and Nikolaev.[9] Typical results are listed in Table I.

For simplicity, we will divide the studied spectral range into three parts. First, we will consider between 1100 and 2200 Å a domain which requires for its most part the use of a vacuum spectrometer and features essentially Na IV and Na V lines; then, between 2200 and 3700 Å, the quartz ultraviolet with the most intense lines of the Na II and Na III spectra; and finally, beyond 4200 Å, an almost totally unclassified spectrum showing a number of well-isolated lines belonging to all possible charge states between 0^+ (neutral) and 5^+.

1100–2200-Å Region

In this wavelength range at optimum resolutions we are able to distinguish two lines distant from 2.5 Å. This is clearly inadequate for good spectral identifications. At low energies ($E < 700$ keV) one might even say that the problem is unsolvable because lines arising from several states of charge overlap at any given wavelength. The only solution was to increase the energy in order to reduce the Na III component of the beam and enhance the excitation of spectra of higher charge states. New trouble arises, however, from the fact that Na IV and Na V spectra are as yet unclassified in that spectral range.

Our spectroscopic results are then limited to the observation of a few tabulated multiplets of Na III ($3p$-$3d$ transition array) and to a tentative classification of a few terms arising from the $3s$, $3p$, and

TABLE I. Calculated equilibrium distribution of charge in the beam.

Nature of target	Incident Na^+ energy (MeV)	Average ion charge	Equilibrium charge distribution 0^+	1^+	2^+	3^+	4^+	5^+
solid	0.5	1.8	0.09	0.30	0.40	0.18	0.03	
carbon	1.8	3.1		0.04	0.21	0.40	0.29	0.05
helium	0.5	1.1	0.20	0.42	0.33	0.05		
gas	1.8	2.4	0.01	0.12	0.38	0.34	0.15	

$3d$ configurations of Na IV and Na V.

Three multiplets of Na VI classified in the recent N.B.S. compilation[10] should also appear in our spectral range. At 1.8 MeV, two strong lines are observed at 1551 and 1608 Å which coincide with the strongest transitions of the $3s\,^3P^0$-$3p\,^3P$ and $3p^3\,P$-$3d^3P^0$ multiplets. Their intensity variation with energy is indeed different from that of the Na V lines, but since no other Na VI line could be detected beyond 1800 Å their identification remains doubtful.

The Na V spectrum is intense at 1.8 MeV when the Na^{4+} component should represent about 30% of the beam. As a general rule the identification of beam-foil spectra is greatly simplified when the recording of several isoelectronic ions can be compared: The same levels are populated and the same multiplet structure is observed. For our study of Na V, we relied on the work of Druetta and Poulizac[11] on O II and Denis *et al.*[12] on Ne IV. The comparison of the recordings was used to check the results obtained by isoelectronic extrapolation of the energy levels.[13]

A few $3s$ and $3d$ levels have already been classified by Söderqvist,[14] but the $3p$ levels are observed for the first time. As indicated on Fig. 2, two multiplets are tentatively attributed to the sextet system which was completely unknown. In the quartet system the position of the $3p^4P$ level is fairly well established since it is now connected with three previously tabulated levels. Although the fine structure could not be resolved in our experiment, the identification of the two strong multiplets at 1891–1910 Å and 1551–1560 Å seems to be justified by isoelectronic comparison. Some uncertainties remain, however, with respect to the $3p^4S$ level because the two lines used for its classification are seriously blended with other transitions of the doublet system. The situation is even more complex in the last system, where three different core configurations are possible; identifications are given only tentatively.

The Na IV spectrum has been observed under the best conditions at 1.2 MeV. Early investigations based on rather poor recordings at low energy have already been published in a brief note.[3] We are now able to improve these results and correct some of our assumptions. Although none of the observed lines are tabulated in standard references, the extrapolation of energy levels along the isoelectronic sequence predicts that a number of $\Delta n = 0$ transitions (with $n = 3$) are present in the observed spectral range. Our research in that direction benefited from the extensive studies on the first member of the sequence recently carried out at Lund.[15,16] The results of Denis *et al.*[12] on the beam-foil spectroscopy of Ne III were also used for comparison purposes.

We can classify nine multiplets in that manner, including all the strong lines of the spectrum. Intense transitions belonging to the quintet system were recorded for the first time, but in distinction to the neon case we have not been able to detect and/or classify any transition between triplet levels with a $2s^22p^33p$ core. Of course, the identifications proposed in Fig. 3 need to be confirmed by classical spectroscopy.

2100–3700-Å Region

The use of the end-on lens system (c on Fig. 1) turned out to be quite useful in that wavelength range and resolutions as good as 1.5 Å at 3000 Å were obtained. Prominent spectral features are already apparent at low energy: Na II lines are strongest around 500 keV and Na III transitions have

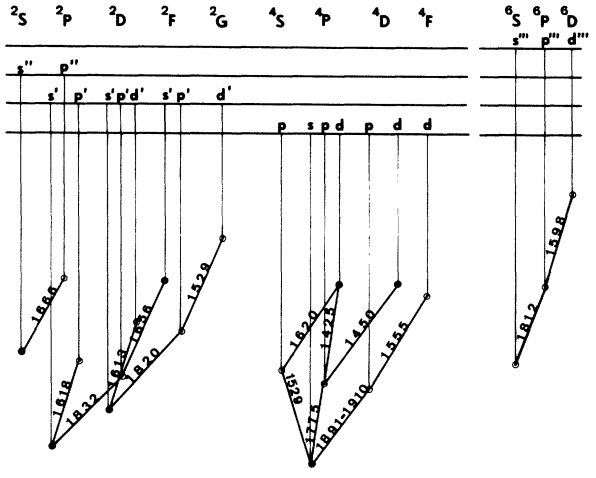

FIG. 2. Tentative assignments in the Na V spectrum. Levels which were previously tabulated are indicated with a dot; new levels with a circle.

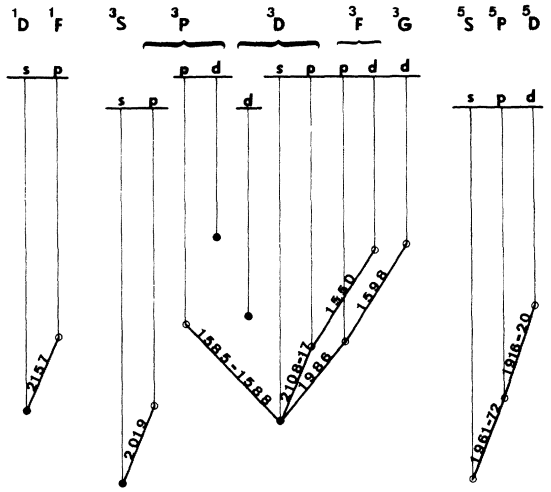

FIG. 3. Tentative assignments in the Na IV spectrum. Levels which were previously tabulated are indicated with a dot; new levels with a circle.

a maximum intensity at 800 keV. Lines of higher charge states are either absent or only weakly excited. Several lines attributed to Na V were however detected (see Fig. 4), including one broad unclassified multiplet around 2980–2990 Å (not shown on the figure) which, on the basis of isoelectronic comparison argument, must correspond to the $3s^2P$-$3p^2S$ Na V multiplet.

Our main results however are concerned with the low-energy observation of the well-known spectra of Na II and Na III. Among tabulated Na II lines, we observed most of the $3s$-$3p$ transitions, a large number of $3p$-$3d$, and a few $3p$-$4s$.

On the other hand, our results in Na III compare favorably with the Ne II observations of Denis *et al.*[17] (see Fig. 4). An important remark to be drawn from that comparison concerns two intense lines at 2387 and 2395 Å which were considered since the early work of Frisch[18] as unclassified Na II lines. Our very first observations on the subject[3] revealed however that they were Na III transitions which correspond probably to the $3s'^2D$-$3p'^2F$ multiplet of Na III. Such a new identification, if it is confirmed by accurate measurements of classical spectroscopy would imply a large revision of the accepted classification by Tomboulian.[19] Not only the $3p'^2F$ levels should be shifted but also the $3d'^2F$ and the $3d'^2G$ levels and 12 lines of Tomboulian's original list would have to be reclassified.

Similar issues are raised by two other strong unclassified lines at 2144 and 2140 Å which are definitely identified on our recordings as Na III transitions. They are in close correspondance with two lines of Ne II belonging to the $3p'^2F$-$3d'^2G$ and $3p^4D^0$-$3d^4F$ multiplet, respectively.

In view of the preceding remarks, such a revised assignment for the $3d'^2G$ level in Na III can indeed be considered. With respect to the $3d^4F$ level, Tomboulian has already pointed out that the $3d^4F_{9/2}$ state could not be classified properly in his level scheme.

At least our results emphasize the need for a second study of the Na III spectrum with special care given to the classification of the $3d$ levels.

Visible Spectrum up to 6000 Å

In this spectral region we repeated the experiment by Brown *et al.*[2] in order to check their surprising results and if possible gather new informations on the origin of the 70 unclassified lines mentioned earlier.

A first step in that direction was to rule out impurity lines. On the Brown's wavelength list, an intense line at 5039 Å, which does not show up on our spectra, coincides with a tabulated transition in C I. Another line, quoted by Brown at 4863.8 Å, corresponds on our own recordings to the 4863-Å line which is attributed to H_β.

For charge-state identification purpose we have studied carefully the intensity variations of the lines with energies of incident beam ranging from 500 keV up to 1.8 MeV.

With the end-on mirror system [Fig. 1(c)] we

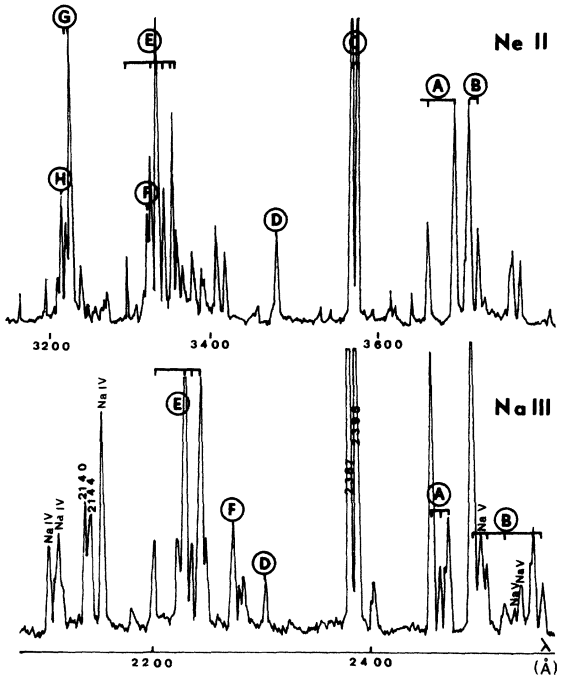

FIG. 4. Comparison of the Ne II and Na III spectra as excited by beam foil:

A: $3s^2P$-$3p^2D^0$	E: $3s^4P$-$3p^4D^0$
B: $3s^4P$-$3p^4P^0$	F: $3s^2P$-$3p^2P^0$
C: $3s'^2D$-$3p'^2F$	G: $3p'^2F^0$-$3d'^2G$
D: $3s^2P$-$3p^2S^0$	H: $3p^4D^0$-$3d^4F$

were able to resolve lines distant by no more than 2 Å. When comparing spectra recorded with this system one must be aware of possible spurious variations of intensity arising in fact from differences in mean lives and not from variations in the excitation functions. In the present case this should not affect our conclusions since measurements have shown later that the mean lives of the considered lines are all of the same order of magnitude and rather long.

Our identifications were greatly simplified by the previous work of Tsui *et al.*[20] on Na II. They classified numerous lines of the $3d$-$4f$ transitions array between 4200 and 4600 Å. At 500 keV, these lines were quite intense on our spectrum and their intensity variations with energy could then be used as reference for charge-state identification of other multiplets. Further information was also obtained from isoelectronic extrapolation of the results of Persson and Minnhagen[21] on Ne II. Several lines observed with good intensity at 800 keV were identified in that manner with the $4f$-$5g$ transitions of Na III.

Our results between 4200 and 4700 Å are summarized in Table II. Most of the former discrepancies between the beam-gas and beam-foil spectra are simple consequences of the density effect (see Table I). They eventually disappear when the beam-foil experiment is carried out at sufficiently low energy. Also, from Table I one sees that the very intense line at 4649 Å, which was not observed by beam-gas excitation at 1 MeV, must be attributed to Na IV.

Above 4700 Å, the sensitivity of our detection system decreases severely. With the exception of the line at 5039 discussed before, all the lines quoted medium or intense in Brown's list are observed. Their charge state is 1^+, except for two multiplets at 4930–4945 Å and 5292–5296 Å which increase drastically with the beam energy and are consequently attributed to Na V. No terms are known in these ionic spectra that could give rise to the lines observed.

Finally, toward the upper limit of our spectral range, the Na I D transitions are recorded at low energy.

IV. ANALYSIS OF EXCITATION DECAYS

As indicated before, the main advantage of the beam-foil technique is that the influence of secondary effects can be kept very small. The observed light is almost entirely due to spontaneous radiative decays of excited states. With beams of measured velocity, the time history of each particle can be related to the point downstream from the foil at which it is detected.

From such simple remarks it appears that beam-foil excitation is well suited for mean-life measurement purpose. There are, however, two inherent difficulties connected with blending and cascading effects. Indeed, very poor spectral resolutions are obtained with the basic side-on system which must, however, be used in order to get good

TABLE II. Wavelength, intensity, and tentative identification of the lines observed in the visible with the "side-on" mirror system (4200–4700 Å). Underlined wavelengths were previously tabulated in Ref. 2. Intensity: I = intense, M = medium, W = weak, V = very.

Wavelength Å	Intensity 0.5 (MeV)	Intensity 1.0 (MeV)	Charge	Transition
4294	W		1	$3d$-$4f$
4310	W		1	$3d$-$4f$
4313	W		1	$3d$-$4f$
4323	W		1	$3d$-$4f$
4376	W		1	$3d$-$4f$
4388	VW		1	$3d$-$4f$
4393	VI	VW	1	$3d$-$4f$
4405	I	W	1	$3d$-$4f$
4408	VW	M	3	
4415	VW	M	3	
4430		W		
4438	M	M	2+3	
4442	M	M	2+3	
4447	VI	M	1	$3d$-$4f$
4455	I	W	1+2	$3d$-$4f$, $4f$-$5g$
4460	M	M	2	$4f$-$5g$
4466	I	M	2	$4f$-$5g$
4473	M	M	2	$4f$-$5g$
4479	M		1+2	$3d$-$4f$, $4f$-$5g$
4482	VI	M	1	$3d$-$4f$
4490	VI	M	1	$3d$-$4f$
4497	M	W	1+2	$4f$-$5g$
4500	W		1	$3d$-$4f$
4504	W		1	
4510	I	M	1+2	
4519	M	W	1+2	
4525	W		1	$3d$-$4f$
4529	W		1	
4534	M	W	1	$3d$-$4f$
4537	W		1	$3d$-$4f$
4542		W		
4546	W		1	$3d$-$4f$
4552	W		1	$3d$-$4f$
4562		W	2	
4571	VW	W	2	
4584	W	M	1+3	
4596		M	3	
4603		M	3	
4608		M	3	
4613		M	3	
4630		VW	2+3	
4649	VI	VI	3	
4678	W	M	3	
4684	M	M	2	
4686	VW	M	3	
4688	VW		1	

TABLE III. $3d$ levels in Na II.

Upper level Core	Upper level Outer electron	Transitions Wavelength (Å)	Transitions Intensity	Cascade (nsec)	Level mean life (nsec) Our result	Level mean life (nsec) Other measurement[a]
	$3d(\frac{3}{2})_2$	3080	M(b)[b]	18	4.7	
$2p^5\,^2P(\frac{1}{2})$	$3d(\frac{5}{2})_3$	3054	I(b)[b]	19	4.5	
	$3d(\frac{5}{2})_2$	3037	M	25	4	
	$3d(\frac{3}{2})_1$	3079	I(b)[b]	18	4.7	
	$3d(\frac{5}{2})_3$	3074	M	17	3.3	
		2901	VW	17	3.3	
	$3d(\frac{5}{2})_2$	3078	I(b)[b]	18	4.7	
		2938	W	26	4.9	
$2p^5\,^2P^0(\frac{3}{2})$	$3d(\frac{7}{2})_3$	2980	M(b)[b]	30	3.8	
	$3d(\frac{7}{2})_4$	2951	VI	5.4; 32	2.4	4.3
	$3d(\frac{3}{2})_2$	3258	W	27	2.9	4.2
		2661	VW	22	3.1	
	$3d(\frac{1}{2})_1$	2672	W	22	2.6	3.2
	$3d(\frac{1}{2})_0$	2678	VW	•••	3.7	

[a]Reference 5.

[b]b: blending possible.

time resolution along the beam. On the other hand, the excitation processes in the foil are complex and clearly not selective in character. The excitation of highly excited states seems to be favored and transitions from higher-lying levels to the level of interest can seldom be neglected.

As a consequence, the recorded decay curves are, in general, multiexponential instead of singly exponential, and a curve-fitting procedure must be used to extract the mean lives involved.

Detection of the cascades is favored when several runs can be made at different energies. This was the case for Na II and Na III transitions which in our experiment were recorded both at 500 and 800 keV. The velocity of the impinging beam was deduced from the calibration of the bending magnet using an NMR probe and from experimental results of Fastrup *et al.*[22] for the energy losses in the foil. Blending is thought to occur for about one-half of the lines of interest. Indications of their decay-curve resolution are only recorded in the following tables if there is no other measurement of the lifetime of the upper level. We will concentrate on the interpretation of the other half of the data which is

TABLE IV. Levels with $n=4$ in Na II.

Upper level Core	Upper level Outer electron	Transitions Wavelength	Transitions Intensity	Cascade (nsec)	Level mean life (nsec) Our result	Level mean life (nsec) Other measurement[a]
	$4s(\frac{3}{2})_2$	2611	M	19	2.4	2.9
	$4f(\frac{7}{2})$	4481	VI(b)[b]	30	4.7	
$2p^5\,^2P(\frac{3}{2})$	$4f(\frac{5}{2})$	4396	I(b)[b]	32	5.1	
		4491	I(b)[b]	35	4.5	
	$4f(\frac{3}{2})$	4405	I	26	5	
	$4f(\frac{3}{2})$	4509	M	26	4.8	
$2p^5\,^2P(\frac{1}{2})$	$4s(\frac{1}{2})_0$	2531	W(b)[b]	•••	5.3	
	$4f$	4447	I	32	4.1	
		4455	I	33	5.5	

[a]Reference 5.

[b]b: blending possible.

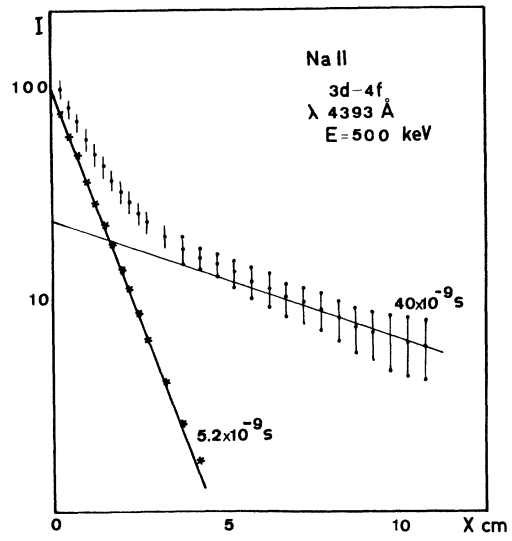

FIG. 5. Decay of the Na II line at 4393 Å.

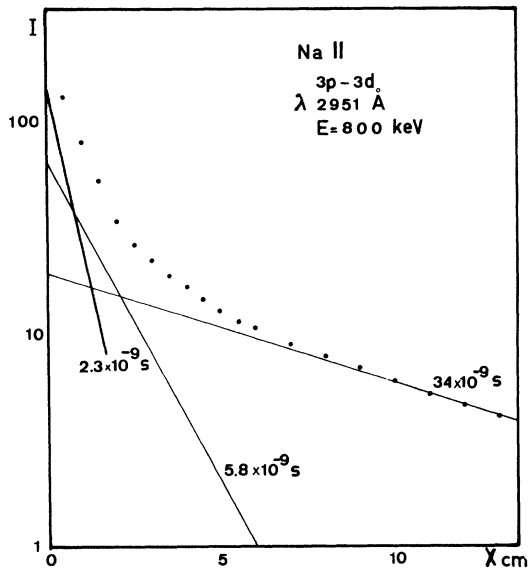

FIG. 6. Decay of the Na II line at 2951 Å.

affected only by cascades.

Mean Lives in Na II

A detailed discussion of the cascade problem has been carried out at the Second International Conference of Beam-Foil Spectroscopy held at Lysekil, Sweden. At that time our results on the Na II $3p$ levels were proposed as a feasible example in cascade corrections. Great discrepancies with previously published measurements[4] were noted, whereas a good agreement is obtained with new refined theoretical data.[23] The interested reader is refered to the proceedings of the conference[24] for

TABLE V. $3p$ levels of Na III (core: $2s^2\,2p^4\,{}^3P$).

Level	J	Transition Wavelength (Å)	Intensity	Cascade (nsec) Grow in Short	Long	Level mean life (nsec) Our result	Other measurement[a]	Theory[b]
$3p^4P^0$	$\frac{5}{2}$	2554	M	1.4		5.4	5.8	4.18
	$\frac{3}{2}$	2563	M	1.7		5.2	6	4.22
		2475	M	1.2		5.5	5.8	
	$\frac{1}{2}$	2510	M			5	5.8	4.18
$3p^2D^0$	$\frac{5}{2}$	2459	VI	2.1	11	3.1	5.1	3.33
	$\frac{3}{2}$	2406	VW			4.3	4.3	3.44
		2469	M			4.1	4.4	
$3p^2S^0$	$\frac{1}{2}$	2310	W		11	2.9	5.3	2.94
$3p^2p^0$	$\frac{3}{2}$	2232	VI(b)[c]		23	3.7	4.1	2.57
		2285	VW			3.5		
	$\frac{1}{2}$	2278	W(b)[c]			3.1	2.9	2.7
		2226	W(b)[c]			3.5		
$3p^4D$	$\frac{7}{2}$	2230	VI(b)[c]		23	3.7		2.7
	$\frac{5}{2}$	2247	I		13	3.3	4.7	2.86
		2203	VW		14	3.4		
	$\frac{3}{2}$	2251	W		13	2.9		
	$\frac{1}{2}$	2239	W		11	3.2		2.78

[a]Reference 5.
[b]Reference 10.
[c]b: blending possible.

TABLE VI. Decay of the unclassified transitions observed in Na III.

Measured wavelength (Å)	Decay constants (nsec) Upper-level mean life	Cascade Short	Cascade Long	Tentative identification
2140	3.5			$3p^4D^0$-$3d^4F$
2143	3.6			$3p'^2F$-$3d'^2G$
2387	3.25	1.9	11.5	$3s'^2D$-$3p'^2F$
2395	3.7	2	15	$3s'^2D$-$3p'^2F$

further details.

In the present paper our results in Na II are concerned with the mean lives of several $3d$, $4s$, and $4f$ levels which are given in Tables III and IV. The main interest in this set of data is to confirm within the experimental uncertainties the model which has been used for the resolution of the $3p$-levels decay curves.

Not to mention direct excitation, the $4f$ levels are strongly populated by cascades from higher-lying levels through undetected red or infrared transitions with long lifetimes. The decays of the lines originating from the $4f$ levels have, consequently, a two-component structure (see example in Fig. 5) and they populate in turn the $3d$ levels. Neglecting other possible cascade schemes, the $3p$-$3d$ transitions should then decay in a three-exponential mode and the $3s$-$3p$ in a four-exponential mode. This is precisely what we observed in a few favorable cases, e.g., Fig. 6.

It is difficult, however, to resolve either graphically or numerically (by least-squares fit) exponentials which do not differ in exponent by more than a factor of 1.5.[25] This is especially so when the experimental curves are plagued with a large dc noise, as indicated in Fig. 5. Consequently, most $3p$-$3d$ transitions were fitted well within experimental uncertainties with only two exponentials, and many $3s$-$3p$ transitions with only three. The error introduced on the mean lives of interest is difficult to evaluate. From what we just said, it can be as high as 50%, and indeed on the $3d$ levels we notice a disagreement with the previous measurements of Andersen *et al.*[5] which is of that order of magnitude. However, our results should rather represent an improvement over their treatment since in their paper they essentially disregarded a cascade analysis of their data.

With respect to the $4s$ and $4f$ levels, the accuracy of the decomposition is certainly better since there is no reason in that case to suspect cascades with short mean lives to interfere with the resolution of the level mean life.

Mean Lives in Na III

We pointed out the close parallel to be drawn between our spectroscopic observations in Na III and the results of Denis *et al.*[17] in Ne II. While measuring the mean lives of the $3p$ levels, one must expect important cascade contributions to arise from the $3d^2D$, $3d^4P$, $3d^4D$, and $3d^4F$ levels. This effect was apparently entirely neglected in the previous set of measurements by Anderson *et al.*,[5] since no mention is made in that case of the resolution of the decay curves. By carefully recording the decays at large distances from the foil (up to 15 cm), we tried to measure at least the long component of the cascade which is known to introduce the largest correction on the measured mean life.

For a final comparison, we mention in Table V the theoretical results calculated in the Coulomb approximation and cited by Wiese *et al.*[10] For lines which appear cascade free in our treatment, our result is in good agreement with Anderson *et al.*[5] and is always larger than the theoretical value by a factor of the order of 20%. However, whenever we have detected a cascade the situation is reversed, and our result is then in much better agreement with the theory. Before definite conclusions can be drawn, further theoretical work is needed in order to check how good the Coulomb approximation should be in that case.

We listed in a separate table (Table VI) the results concerning the decay of the four untabulated lines attributed to Na III which were discussed earlier (see Sec. III).

Decay of Na IV Transitions

As mentioned before, most of the observed Na IV lines were previously untabulated. In order to support our identifications, and to start with our charge-state identifications, we recorded the decay of eight out of the nine tentatively classified multiplets.

In the vacuum ultraviolet only three strong groups of unresolved lines could be measured with poor statistics. Better results were obtained in the quartz ultraviolet, where all the lines appeared cascade free with short decay constants, which were all of the same order of magnitude (Table VII).

TABLE VII. Measured decay constants for the Na IV multiplets.

λ_{vacuum} (Å)	Decay constant (nsec)	Tentative identification
1585–88	1.5	$3s'^3D$-$3p'^3P$
1616–20	2	$3p^5P$-$3d^5D$
1961–72	3.7	$3s^5S$-$3p^5P$
1986	2.7	$3s'^3D$-$3p'^3F$
2019	3.4	$3s^3S$-$3p^3P$
2108	3.9	$3s'^3D$-$3p'^3D$
2117	3.9	$3s'^3D$-$3p'^3D$
2157	4.2	$3s'^1D$-$3p'^1F$

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