molecular targets, obtained by taking allowance for phase. For the N_2 molecular target we compare the cross section with and without the phase factor. It is observed that no significant change in cross section results from the inclusion of the phase factor. The change is negligible for energies beyond 300 keV. Below 300 keV, the maximum deviation in the magnitude of the cross section with and without the phase factor is within 10% for N_2 molecular targets, whereas for the cases of H_2 and O_2 the deviation is still less. For He incident on the H_2 molecular target, the present calculation in the low-energy region agrees well with the measurements of Gilbody *et al.*,[11] whereas for the N_2 molecular target, the calculated cross sections are much higher than the experimental measurements of Gilbody *et al.*[10]

We find that for almost all the targets (whether atomic or molecular) with higher atomic numbers, the present calculation grossly overestimates the cross section in the region in which the data are available. A similar feature is also observed in Victor's calculation with a H atom as a projectile. As pointed out by Victor,[5] this discrepancy may be due to the use of the Hartree–Fock coherent- and incoherent-scattering functions to describe the target systems. Further, for the molecular targets the consideration of the phase through an outside factor within the framework of the separated-atom approximation should not be good. Moreover, the present calculation does not make any allowance for the relativistic effects, although they become important at high energies. The experimental measurements for these and other targets over a wide energy range, especially at high energies, are needed in order to assess the various theories for the electron loss from the passage of atoms through atomic and molecular target systems.

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PHYSICAL REVIEW A VOLUME 7, NUMBER 1 JANUARY 1973

Radiative Mean Lifetimes of Levels in K II and Rb II

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Beam-foil spectra of K II and Rb II were obtained at 600-keV bombarding energy. The lines identified in the spectrum of K II and the measured lifetimes of four $4p$ levels, three $4p'$ levels, and one $5s$ level of the ion are presented and compared with other experimental results. The first experimental results on the lifetimes of three $5p$ levels, one $5p'$ level, and two $5d$ levels of Rb II and the lines identified in the beam-foil spectrum of the ion are given.

In a continuing program of measuring atomic lifetimes by the beam-foil method, we obtained the mean lifetimes of some levels in K II and Rb II. A general description of the experimental apparatus has been presented by Assousa *et al.*[1] In Sec. I we present those details of the experiment relevant to this paper only. In Sec. II we present the results of our measurements, make an estimate of the uncertainties involved and compare our results with those of other workers.

I. EXPERIMENTAL METHOD

Singly ionized atoms of potassium and rubidium of natural isotopic composition were accelerated to 600 keV and analyzed by a 7° deflection magnet before impinging on the carbon foil of thickness

TABLE I. Lines detected in the beam-foil spectrum of potassium at 600 keV.

Wavelength (nm)	Identification	Upper energy level (cm^{-1})	Intensity[a]
334.5			M
335.8	K III	238455.1	M
336.3	K III	243947.4	V.S.
337.3			M
338.0	K II?	217726.4	S
338.4	K II	217066.3	M
	K II	219196.2	
342.1	K III	243448.2	S
	K III	237912.2	
343.3			W
344.0	K II	219196.2	M
346.8	K III	237512.2	M
347.5			W
348.1	K II	215404.9	W
	K III?	241443.5	
349.5			M
351.4	K III	237912.2	M
353.1	K II	194776.1	S
354.8			W
355.3			W
357.6			W
360.8	K II	215855.8	M
361.8	K II	190134.8	M
368.2	K II	189661.7	S
376.7	K II	189772.0	S
378.3	K II	189661.7	V.S.
379.9	K II	212992.3	M
381.7	K II	212575.5	V.S.
384.9			M
385.7			M
386.1	K II	212575.5	S
387.3	K II	189243.7	M
387.8	K II	21508.8	M
389.8	K II	188154.8	V.S.
	K II	190134.8	
392.2	K II	214727.0	W
392.6	K II	212992.3	W
393.2			S
394.2	K II	215018.8	W
395.4	K II	189722.0	S
396.7	K II	190134.8	M
397.2	K II	189661.7	S
398.5			M
399.5	K II	187531.1	S
400.1	K II	190134.8	S
401.2	K II	188154.4	S
410.7	K II	215018.8	W
402.5	K II	212992.3	W
404.2	K II	189661.7	S
407.0			M
408.0			M
408.9			M
409.3	K II	212575.5	M
410.9	K		S
411.5	K II	187531.1	S
412.9	K III?	238455.1	W
413.4	K II	186685.1	S
414.4			S
414.9	K II	187531.1	S
	K II	189243.7	

TABLE I. (*Continued*)

Wavelength (nm)	Identification	Upper energy level (cm^{-1})	Intensity[a]
418.6	K II	186388.5	V.S.
419.4			S
419.8			S
420.5			M
420.7			M
421.3			M
421.9			S
422.3	K II	190134.8	S
422.5	K II	188154.4	S
422.6	K II	188154.4	S
424.5			W
425.8			W
426.3	K II	186685.6	V.S.
427.1			M
428.9	K II	189772.0	M
429.7			S
430.5	K II	188154.4	S
	K II	212992.3	
430.9	K II	189661.7	S
431.8			M
432.5			M
434.0	K II	187531.1	S
435.2			V.S.
436.3	K II	212575.5	W
437.7			M
438.8	K II	189243.7	V.S.
442.3	K II	187531.1	W
445.4	K II	212575.5	M
446.6	K II	187531.1	S
449.2			W
449.9			M
450.6	K II	186685.6	S
451.4			W
453.0			M
457.7			S
458.5			M
459.3	K II?	186685.6	V.S.
459.9			V.S.
461.1	K II?		V.S.
464.2			M
465.2			W
466.2			M
467.6	K III?	262828.0	S
469.7			W

[a] W, weak; M, medium; S, strong; V.S., very strong. Entries with wavelength column blank are alternate identification to preceding line. The energies of the $4p$ levels are all less than 200 000 cm^{-1}; those of the $5s$ and $4d$ levels are greater than 200 000 cm^{-1}.

10 ± 4 $\mu g/cm^2$. The isotopes were not separated. The spectra were photographically recorded on IIa-O plates using the Carnegie image tube spectrograph. The spectral plates were developed with intensity calibration plates exposed through a step-wedge to blue light. Between 340 and 420 nm we used a 1200 lines/mm grating in the second order yielding a dispersion of 14 nm/mm. We employed a 600 lines/mm grating in the second order be-

tween 420 and 500 nm giving 28 nm/mm. We found less than five lines between 500 and 700 nm using the 1200 lines/mm grating in the first order in the spectrum of each ion. These were very weak and, hence, were not measured. The average beam current measured before entering the foil was generally 0.1 μA. At each grating setting we obtained two spectra of about 1-h exposure each, with a narrow slit which had a projected width of 15 μm on the plate. This corresponds to a bandpass of 0.014 nm between 340 and 420 nm and 0.028 nm between 420 and 500 nm. One of these was a foil-excited spectrum for wavelength measurements and for examining the possible presence of blended lines. The other spectrum obtained was excited by He gas filling the target chamber at 10^{-4} Torr with no carbon foil. In this gas-excited spectrum we see lines due to both He and the accelerated ion, which can be differentiated by their relative inclinations with respect to the comparison spectrum. The wavelength shift for known lines of the bombarding ions, here referred to as beam lines, was measured relative to the target gas lines and was used to correct the Doppler-shifted lines. The intensities of some of the beam lines were measured at several distances from the foil to check systematic effects such as vignetting, which could result in spurious lifetime values. We found no such effects which could contribute more than 5% to the errors in the measured lifetimes.

Spectral plates for mean-lifetime measurements were exposed with the slit fully open ($\approx$0.4 mm on plate). This corresponds to a band pass of 0.56 or 1.12 nm depending on the dispersion. The slit-to-plate magnification is 0.1. For some wavelength intervals spectra were obtained at two different magnifications by changing the distance between the target chamber and the spectrograph. The beam-to-slit magnifications were 0.39 and 0.26. The total magnification of the system was determined in each case by placing a calibrated line pattern at the foil position and photographing it through the spectrograph. It may be noted that the width of the wide-open slit projected on the beam was either 15 or 10 mm, depending on the spectrograph-to-target-chamber distance. The spatial resolution of the spectrograph is 35 μm on the plate. If the slit width used is sufficiently narrow ($\leq$25 μm on the plate) the wavelength resolution of the instrument is 0.05 or 0.1 nm, depending on the dispersion. The length of the beam observed was 6 cm. In Tables I and II we present the measured wavelengths, suggested identifications, and eye estimates of intensities of all lines detected in the wavelength range 335–500 nm in the beam-foil spectra of K and Rb, respectively.

The measured wavelengths of the lines were compared with those computed using the energy levels given by Moore.[2] All coincidences within 0.1 nm were examined and only those lines whose parent electron configuration was evident by the detection of other lines from that configuration were attributed to the ion being studied. From

TABLE II. Lines detected in the beam-foil spectrum of Rb at 600 keV.

Wavelength (nm)	Identification	Upper energy level (cm^{-1})	Intensity[a]
343.5	Rb II	186 011	M
344.0	Rb II	163 929	M
346.2	Rb II	185 623	W
349.3	Rb II	187 340	S
352.1	Rb II	185 132	S
353.2	Rb II	164 973	S
	Rb II	193 280	
354.1	Rb II	185 132	W
360.5			V. S.
363.7			W
364.0	Rb II	184 205	M
	Rb II	185 623	
366.3	Rb II	186 011	V. S.
369.9	Rb II	167 637	M
379.7	Rb II	161 205	S
380.1	Rb II	165 095	M
382.6	Rb II	187 340	S
	Rb II	184 842	
380.7			W
383.7	Rb II	184 205	W
384.2			W
384.9			M
392.6	Rb II	179 740	W
394.0	Rb II	158 717	V. S.
397.8	Rb II	163 929	S
399.3			W
400.6			W
401.1			W
402.8			W
408.4	Rb II	165 095	W
410.4	Rb II	164 973	S
413.5	Rb II	167 637	W
419.3	Rb II	158 717	S
424.4	Rb II	156 901	V. S.
427.3	Rb II	156 742	S
428.8	Rb II	163 929	S
429.4	Rb II	158 157	S
437.8	Rb II	179 740	S
453.1	Rb II	165 095	M
453.5			W
454.1	Rb II	180 173	M
457.2	Rb II	156 742	S
462.3	Rb II	165 095	W
464.9	Rb II	164 973	S
475.6	Rb II	179 740	W
477.7	Rb II	154 279	S
478.3	Rb II	163 929	W

[a] W, weak; M, medium; S, strong; V. S., very strong. Entries with wavelength columns blank are alternate identification to preceding line.

this list of identified lines, only those which were clearly not blended were selected for lifetime measurements.

The selected lines were scanned with a densitometer. The dimensions of the densitometer slit projected on the plate were 35×20 μm with the length of the slit parallel to the beam direction and the width parallel to the dispersion. The scans were parallel to the dispersion direction and between each scan the distance from the foil position was incremented by 50 μm on the plate. It may be noted that 35 μm on the plate along the beam direction corresponds to 0.75 and 0.48 nsec for the K^+ ion for the two-spectrograph target-chamber spacings used in recording the spectra, and 1.2 and 0.75 nsec for the Rb^+ ion. These factors take into account the total energy loss of the ions in the carbon foil, computed following Lindhard *et al.*,[3] and Fastrup *et al.*[4]

As noted earlier the total length of the beam photographed was 6 cm. In scanning with a densitometer, the first 2–3 mm of the beam were generally ignored because of the possible influence of light scattered by the foil holder. In addition, in the case of strong lines another 2–3 mm of the beam was ignored because of over-exposure. The line was traced as far downstream as possible before the intensity became too low. Generally the length of the beam scanned was between 2.5 and 4 cm. In other words, most of the lines were scanned over a time interval which is 2–3 mean lifetimes long.

II. RESULTS AND DISCUSSION

Potassium

In Table III we present the lines we identified in the spectrum of K II and our measurements of the lifetimes of several levels. For comparison the experimental results of Berry *et al.*[5] and Andersen *et al.*[6] are given. Our uncertainty estimates are based on (i) 12% uncertainty due to scatter in results for the same line measured on two or three plates, (ii) scatter of measured intensities about the decay curve resulting in another 12% error, and (iii) 5% error due to uncertainty in the energy loss in the foil. The decay curves were obtained by drawing a straight line by eye, except in the case of the 381.8-nm line, to the data points on a log-intensity versus time-of-flight plot. As noted above the differences between results for the same line measured on two or three plates were as large as our estimated uncertainty for one measurement. It is obvious that the over-all uncertainty is not greatly reduced by more accurate fits to the data points. The over-all uncertainty given in Tables III and IV is the RMS value of the three individual sources given above.

As explained earlier we excluded vignetting as

TABLE III. Mean lifetimes of K II levels.

Level			Lifetime (nsec)			
Upper	Lower	λ (nm)	DTM	Berry *et al.*	Andersen *et al.*	Mean
$2p_2$	$1s_5$	361.9	7.3±1.3			
	$1s_3$	400.1	7.3±1.3	5.4±0.5[a]	9.0±0.5	
	$1s_2$	422.3		7.2±0.7	9.0±0.5[a]	7.2
$2p_3$	$1s_5$	368.2		8.0±0.5		
	$1s_4$	378.3	8.0±1.4		8.8±0.5	8.3
$2p_4$	$1s_3$	414.9			9.0	
	$1s_2$	438.8	9.6±1.7	10.3±0.6	9.0±0.5	9.6
$2p_5$	$1s_4$	376.8	6.2±1.1		6.4±0.5[a]	
	$3d_5$	395.5	6.3±1.1		7.7±0.5	6.7
$2p_6$	$1s_5$	389.8	7.9±1.4	8.3±0.5	9.4±0.5[a]	8.6
	$3d_5$	422.6			9.0	
	$1s_2$	460.9	8.9±1.6			
$2p_7$	$1s_5$	399.5	7.5±1.3			
	$1s_4$	411.5	(7.4)±1.3		9.1	
	$3d_5$	434.0	7.1±1.3	8.8±0.5	8.8±0.6	8.3
	$1s_3$	446.7			8.4	
$2p_8$	$1s_5$	413.5	7.6±1.3		8.8	
	$1s_4$	426.3			8.6±0.5[a]	8.4
	$3d_5$	450.5	8.0±1.4		9.4	
	$1s_2$	494.3			8.8[a]	
$2s_5$	$2p_9$	381.8	2.8±0.5[a]	3.1±0.5[a]	3.9±0.4	3.3

[a]Cascade corrections.

a source of uncertainty. Furthermore, we believe that multiple Rutherford scattering in the foil does not affect our results. The width of the wide-open slit, projected at the beam, is 1.56 or 1.04 cm depending on the beam-to-slit magnification. The width of the beam before entering the foil is 1 mm. Earlier photographs of a 700-keV argon beam incident on a 10-$\mu g/cm^2$ foil showed that at 6 cm from the foil the beam had broadened to 3 mm which is much narrower than the projected slit width. During the gas-excitation mode we were able, clearly, to see the K and Rb beams and convince ourselves that the beam width never exceeded 1 cm. Earlier photographs obtained using neon and argon beams at 700 keV showed us that the beam width without the gas was about one-half as wide as with gas.

Our results agree with those of others within experimental uncertainties but are generally lower especially when compared with the values of Andersen *et al.* Some decay plots are shown in Fig. 1. Similarly the results of Berry *et al.* tend to be lower than those of Andersen *et al.*, and in some cases the values of Berry *et al.* differ from those of the latter by more than the quoted errors. The results for the $2p_2$ level show the largest differences between the three experiments. We note that in our wide-open slit spectra the line at 422.3 nm is blended with another line at 422.6 nm from the $2p_6$ level. We did not detect the presence of long-lived cascade effects in any decay curve except for that of the line at 381.8 nm. Berry *et al.* working at 160 keV detected a long-lived cascade in the above line, but the third group working at intermediate energies did not notice any cascade effects. In regard to lines from other levels we note that neither we nor Berry *et al.* noticed any cascade effects, whereas Andersen *et al.* noticed such effects in a number of lines common to our experiments. Andersen *et al.* point out that these cascades result from the short-lived ($\tau \leq 3.5$ nsec) $4p$-$5s$ and $4p$-$4d$ transitions, and that they are noticeable in the first 6–8 mm of the beam. As noted earlier, we generally ignored the first 4–6 mm of the beam. Furthermore, we see in Table I the lines feeding the $4p$ levels are weak compared to the lines from the $4p$ levels which we studied. Hence, it is not surprising that we did not detect these cascades. The important point is that correction for these cascades can only increase the discrepancy between the results of Andersen *et al.* and of the other two experiments. Finally, none of the three groups has detected any long-lived cascades in the decay curves of lines resulting from the $4p$ levels. It is known[7] that the failure to detect such cascades may be partly responsible for the fact that mean lifetimes resulting from beam-foil experiments generally are larger than those obtained from other kinds of experiments. In this connection we would like to bring to the reader's attention that a preliminary investigation[8] of the beam-foil spectrum of K II between 300 and 550 keV suggests that many of the lines from the $4p$ level may have long-lived cascades ($\tau \approx 20$ nsec). If this turns out to be the case, the results presented here overestimate the true values by about 25%. With this qualifying comment, we present in the last

TABLE IV. Beam-foil spectral lines and mean lifetimes of Rb II.

Upper level energy (cm^{-1})	Wavelength (nm)	Lifetime (nsec)	Upper level energy (cm^{-1})	Wavelength (nm)	Lifetime (nsec)
186 011	343.4		165 095	380.2	
	366.3			453.0	
185 623	346.2			408.4	
	364.0			462.2	
187 340	349.3	2.9±0.5	164 973	353.2	
	382.5			410.4	6.8±1.0
185 132	352.1	3.4±0.5		464.9	7.6±1.1
	354.1		163 929	344.1	
184 205	364.0			397.8	
	383.8			428.8	
180 173	454.1			478.3	
179 740	392.7		161 205	379.7	
	437.7		158 717	394.1	
	475.5			419.3	
167 637	370.0		158 157	429.4	
	413.6		156 901	424.5	6.9±1.0
			156 742	427.3	6.6±0.9
				457.2	8.3±1.2
			154 279	477.6	8.3±1.2

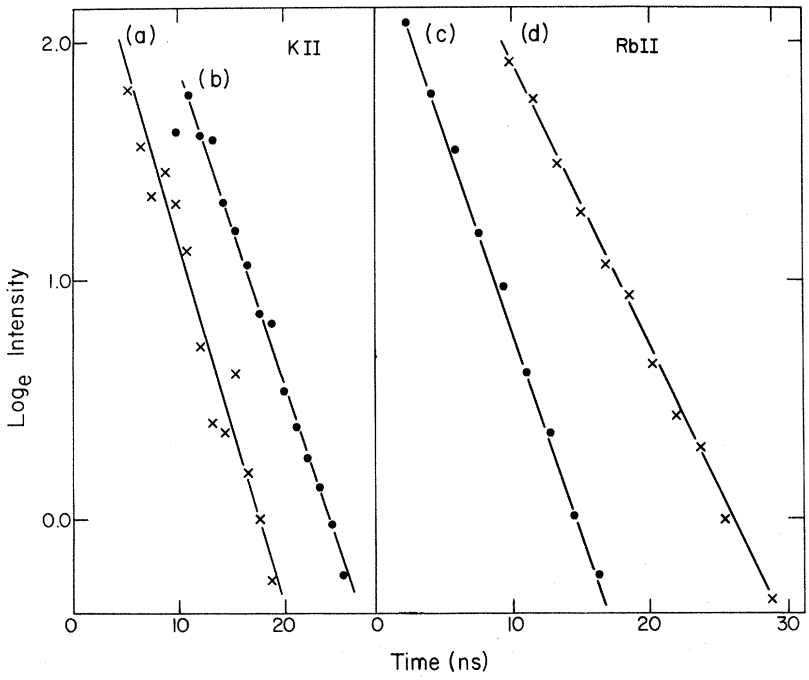

FIG. 1. Measured decay curves for some lines. The wavelength of the lines are (a) 395.5 nm, (b) 400.1 nm, (c) 410.4 nm, and (d) 457.2 nm.

column of Table III the means of the three experiments.

Rubidium

In Table II we present all the lines detected in the beam-foil spectrum of Rb between 340 and 500 nm. Of these 44 lines, we attribute 35 to Rb II. The measured mean lifetimes of some levels are given in Table IV. In this case the deviations of the measured intensities from the decay curves are smaller than in the case of K II. This was due to reduction of the background intensity, intrinsic to the image tube. We estimate the uncertainty of the mean-lifetime value for a single measurement to be 6%. The other uncertainties are the same as before. There are no published results for the $5p$, $6s$, or $5d$ of Rb II, either experimental or theoretical.

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