

THE OPTICAL CONSTANTS OF SOLID CAESIUM

BY J. B. NATHANSON

ABSTRACT

The caesium mirror was prepared by filling a glass cell having two optical glass windows with liquid caesium distilled over in vacuum, the metal then being allowed to solidify. The index of refraction and the coefficient of absorption were determined by the polarimetric method. The caesium on glass mirror was placed in optical contact with the hypotenuse side of a right angle prism so that the light entered one leg and came out of the other. The absolute index of refraction was obtained from the observed value by multiplying the latter by the index of refraction of the glass, the coefficient of absorption remaining the same. The *index of refraction* was found to vary from 0.362 for $\lambda 4550\text{\AA}$ to 0.350 for $\lambda 6800\text{\AA}$, with a minimum value of 0.321 for $\lambda 5890\text{\AA}$. The *coefficient of absorption* increased from 2.37 for $\lambda 4550\text{\AA}$ to 4.34 for $\lambda 6800\text{\AA}$. The *principal angles of incidence and of azimuth* calculated by means of Drude's formulas increased from $55^{\circ}25'$ and $38^{\circ}32'$ respectively for $\lambda 4550\text{\AA}$ to $63^{\circ}20'$ and $40^{\circ}6'$ for $\lambda 6800\text{\AA}$. The corresponding values of the *reflecting power* were 44.2 and 66.1 per cent. The computed reflecting power of caesium in contact with crown glass increased from 48.5 per cent for $\lambda 4550\text{\AA}$ to 63.2 per cent for $\lambda 6800\text{\AA}$. A direct spectro-photometric determination yielded corresponding values of 37.2 and 63.2 per cent, the agreement being best in the yellow and red end of the spectrum.

INTRODUCTION

DURING recent years, the alkali metals, by virtue of their interesting physical and chemical properties, have been the subject of many investigations. The optical constants are especially interesting, for they indicate an index of refraction less than unity and a very high reflecting power in the case of sodium and potassium. As early as 1898, Drude¹ determined the optical constants of molten sodium. Both sodium and potassium in the solid state were studied by R. W. and R. C. Duncan² using the polarimetric method that had been developed by Drude. The reflecting powers of sodium, potassium, and rubidium were studied by Nathanson³ using a photo-electric cell as a photometer. The latter⁴ also determined the optical properties of rubidium by the polarimetric method. Miss Frehafer⁵ investigated the reflection and transmission of

¹ P. Drude, Ann. der Phys. **64**, 159 (1898)

² R. W. and R. C. Duncan, Phys. Rev. **36**, 294 (1913)

³ J. B. Nathanson, Astrophys. J. **44**, 137 (1916)

⁴ J. B. Nathanson, Phys. Rev. **11**, 227 (1918)

⁵ Mabel K. Frehafer, Phys. Rev. **15**, 110 (1920)

ultraviolet light by sodium and potassium, using a photo-electric cell as a photometer. Quite recently the optical properties of sodium-potassium alloys were determined by Morgan⁶ using the polarimetric method.

It was thought desirable to extend our knowledge of the optical properties of the alkali metals by studying caesium. Accordingly the optical constants of caesium were determined.

PREPARATION OF THE CAESIUM MIRROR

The caesium mirror was formed by filling a small glass cell with the metal under vacuum. The insert *M* in Fig. 1, shows an enlarged end view of the cell. This cell consists of a Pyrex glass ring 1.8 cm internal diameter, to which is attached a connecting tube *L* of small bore. The edges of the ring were ground with emery and turpentine until the width

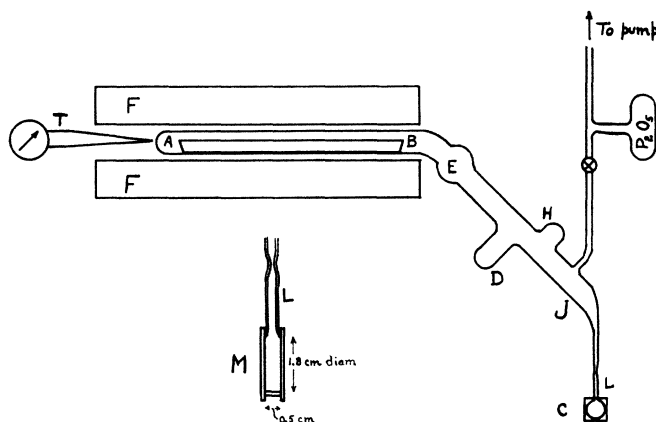


Fig. 1. Arrangement of apparatus for producing a caesium mirror.

of the ring approximated 0.5 cm, and then were polished with jeweler's rouge. After thorough cleansing a glass plate was cemented to each side of the ring by means of "Rock Cement," and the cell was baked for several hours in an electric oven kept at a temperature of about 110°C. It was found that with the cell so made, no difficulty was experienced in maintaining a high vacuum. The glass plates forming the windows of the cell were of high quality optical glass, 1.5 mm thick, and possessing a refractive index of 1.523 for sodium light. Each cell supplied two mirrors for investigation.

The glass cell *C* (Fig. 1) was connected by means of the tube *L* to the Pyrex glass apparatus in which the caesium was prepared. An intimate mixture of freshly prepared calcium filings and caesium chloride was

⁶ R. Morgan, Phys. Rev. **20**, 203 (1922)

placed in an iron boat *B*, 30 cm long. This was then introduced into the horizontal tube and carefully sealed off at *A*. The boat and contents were heated by means of an electric furnace *F*, whose temperature was indicated by the thermo-couple *T*. The apparatus was evacuated by means of a Langmuir pump, the glass being thoroughly baked by applying bunsen flames to all parts.

The furnace was heated slowly to about 425° when first traces of caesium appeared in the condensing chamber *E*. The heating was continued, but the temperature was never allowed to rise above 625°C . The condensed caesium accumulated in the side tube *D*. When sufficient caesium had been collected, the tube *D* was placed in a small electric heater, and the caesium carefully redistilled at a temperature which never exceeded 200°C . By maintaining a burner between *E* and *D* during the redistillation, the caesium vapor was driven down to *J* and then condensed and collected in the cell *C*. The projection *H* acted as a condensing chamber. After the cell was filled with the molten caesium, it was detached by means of a blast lamp at the constriction in the tube *L*. The caesium remaining in the bottom of tube *J* was examined spectroscopically, and found to contain no traces of any impurities.

Some seven cells were filled with caesium, but the results are given only for the two cells whose mirrors seemed most perfect on inspection. The temperature of the laboratory did not exceed 23°C during the investigation, so that the caesium was always in the solid state.

EXPERIMENTAL METHOD AND FORMULAS

The polarimetric method used in this investigation was essentially the same as that employed previously in the study of rubidium.⁴ The apparatus at the disposal of the writer consisted of a large Geneva Society spectrometer, with the customary mounting of nicol prisms and simple Babinet compensator. The positions of the nicols could be read to $6'$, while that of the Babinet compensator to about $5'$. A 6.6 ampere single-filament gas-filled lamp furnished the light which was dispersed by means of a Hilger constant deviation spectrometer.

In order to avoid the disturbance produced by the glass surface of the mirror, the hypotenuse side of a right angle prism was placed in optical contact with the mirror by means of a little cedar oil, whose index of refraction was close to that of the glass. The light polarized in a plane at an angle of 45° with the plane of incidence, was incident normally on one leg of the prism (see Fig. 2), was reflected at an angle of 45° from the caesium-glass surface, and emerged normally from the other leg of the prism. The phase difference of the two components of the elliptically

polarized light and the azimuth of restored plane polarized light were determined by means of the compensator and analyzing nicol.

The glass cell *C* was held against the prism *P* by means of a sliding screw clamp *S*, Fig. 2, and the prism was held in place by brass strips *BB*. The latter were so attached to the prism table *T* that the reflecting surface was over the vertical axis of the spectrometer. This arrangement facilitated the removal and replacement of mirror and prism when observing the zero position of the compensator.

To attain as high an accuracy as possible, a large number of observations were made to determine the phase change and azimuth of the reflected light. The zero position of the compensator was determined for the four positions of the polarizer, ten individual settings being made for each of these four positions. This was repeated for the position of the compensator corresponding to a phase change of 360° . The mirror and

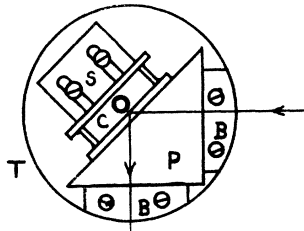


Fig. 2

Fig. 2. Mounting of prism and mirror on spectrometer table.

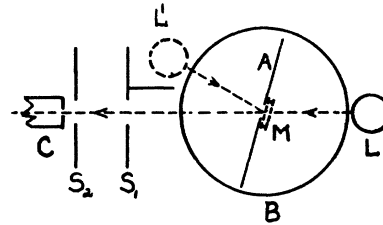


Fig. 3

Fig. 3. Determination of the reflecting power of a caesium mirror by means of the Lummer-Brodhun spectrophotometer.

prism were then set in place, the telescope turned through 90° to receive the reflected light, and the new position of the compensator determined as before. Also for each of the polarizer positions, the positions of the analyzing nicol for total extinction of the light were carefully determined. From the means of all the sets of observations on the analyzing nicol, twice the angle of restored plane polarization was computed.

For the computation of the coefficient of absorption k and the index of refraction n , of the metal, Drude's formulas in the rigorous form were used, since the index of refraction is so low.

$$\begin{aligned} \text{Let} \quad \tan Q &= \sin \Delta \tan 2\psi; \\ \cos 2P &= \cos \Delta \sin 2\psi; \\ S &= \sin 45^\circ \tan P; \end{aligned}$$

where Δ is the phase difference and ψ the angle of azimuth. The coefficient of absorption k is then given by

$$k = \tan \frac{1}{2}X \quad (1)$$

where $\tan X = S^2 \sin 2Q / (S^2 \cos 2Q + \sin^2 45^\circ)$.

The index of refraction n was then evaluated by means of the equation

$$n^2 = (S^2 \cos 2Q + \sin^2 45^\circ) / (1 - k^2). \quad (2)$$

The reflecting power R for normal incidence is given by

$$R = \frac{n^2(1+k^2) - 2n + 1}{n^2(1+k^2) + 2n + 1}. \quad (3)$$

RESULTS

The results for caesium in contact with crown glass are given in Table I. Only the data for the four best mirrors are listed.

TABLE I

Caesium in contact with crown glass

λ	Polarimetric method								Spectro-photometric	
	Mirror	Δ	2ψ		n	k	R	O	R	
4550 A	No. 2	103°	29'	80°	2'	0.251	2.23	0.465	0.388	
	3	105	53	79	59	0.252	2.44	0.481	0.388	
	8	100	15	80	36	0.242	2.00	0.455	0.364	
	9	104	19	81	55	0.205	2.81	0.540	0.396	
	mean	103	29	80	38	0.238	2.37	0.485	0.384	0.372
4890	2	104	44	81	11	0.223	2.63	0.515	0.471	
	3	104	30	81	10	0.223	2.60	0.512	0.463	
	8	104	11	80	21	0.243	2.36	0.481	0.433	
	9	107	14	82	07	0.201	3.22	0.567	0.480	
	mean	105	10	81	12	0.223	2.70	0.519	0.462	0.457
5400	2	110	10	81	49	0.212	3.39	0.573	0.533	
	3	110	59	81	40	0.217	3.40	0.571	0.532	
	8	108	52	80	56	0.232	2.96	0.535	0.536	
	9	111	36	82	38	0.194	3.90	0.612	0.565	
	mean	110	24	81	46	0.214	3.41	0.573	0.542	0.541
5890	2	110	13	82	18	0.200	3.61	0.593	0.564	
	3	111	8	81	40	0.217	3.42	0.574	0.566	
	8	112	59	81	41	0.222	3.57	0.580	0.589	
	9	115	33	82	37	0.204	4.21	0.627	0.613	
	mean	112	28	82	4	0.211	3.70	0.594	0.583	0.586
6410	2	111	51	82	11	0.206	3.70	0.596	0.612	
	3	112	53	81	58	0.214	3.68	0.592	0.625	
	8	118	25	81	56	0.233	4.01	0.611	0.626	
	9	118	16	83	4	0.201	4.66	0.654	0.637	
	mean	115	21	82	17	0.214	4.01	0.613	0.625	0.629
6800	2	116	1	82	22	0.212	4.10	0.619	0.618	
	3	121	55	81	54	0.251	4.12	0.617	0.620	
	8	122	11	82	11	0.245	4.28	0.630	0.630	
	9	121	26	83	6	0.213	4.84	0.663	0.638	
	mean	120	23	82	23	0.230	4.34	0.632	0.627	0.632

The mean results for n and k are plotted in Fig. 4. The index of refraction seems to be a minimum in the visible spectrum for a wave-length of 5890 Å. The coefficient increases steadily from a value of 2.37 for $\lambda 4550$ Å to a value of 4.34 for $\lambda 6800$ Å.

The values for the computed reflecting power R are listed in column seven of Table I. It was thought desirable to compare these computed results with the values obtained more directly by means of a Lummer-Brodhun spectrophotometer.

The arrangement of apparatus is shown in Fig. 3. An ordinary spectrometer B was placed in front of the collimator C of the spectrophotometer. The telescope was removed, and in its place was mounted a white light bulb L . In place of the spectrometer prism table was mounted a screen A painted a dull black color and containing a circular aperture slightly smaller in diameter than the caesium mirror. By means of small clamps, the mirror was mounted right behind the circular aperture and over the center of the spectrometer. Screens S_1 and S_2 served to prevent stray light from reaching the collimator of the spectrophotometer.

The procedure in observation was as follows. With the mirror removed and the light at L ten settings were made with the spectrophotometer. The mirror was then mounted at M , the light turned through an angle of 180° minus twice the angle of incidence, to position L' . Observations were then made on the reflected light. The reflecting power of the caesium glass mirror is given by the ratio of the sector readings after and before reflection.

In order to compute the reflecting power of caesium in contact with glass, allowance must be made for reflection at the front face of the glass, multiple internal reflection, and absorption in the glass itself. A formula to correct for these disturbances had been previously³ developed in the study of the reflecting powers of the alkali metals.

Let O = the observed reflecting power of the mirror (metal plus glass);

r = reflecting power of the front glass surface (air to glass to air);

r' = reflecting power of glass surface (glass to air to glass)

t = transmission power of the glass plate per single passage of the light.

The reflecting power R of the caesium in contact with glass is given by

$$R = (O - r) / [t^2(1 + Or' - r - r')]. \quad (4)$$

The angle of incidence of the light on the front face of the glass surface was kept at 20° throughout the investigation with the spectrophotometer. From previous data,³ r was taken as 0.042, r' as 0.035, The transmission t was redetermined and found to be 0.99. The variation of these quantities with wave-length is quite negligible. The actual angle of incidence

of the light on the caesium was about 13° . A test showed that there is very little variation in the reflecting power with the angle of incidence up to 30° , so that the reflecting power of caesium as computed may be taken as the value that would have been obtained for normal incidence. The values of O are given in the eighth column of Table I, while the values of R as computed by Eq. (4) are shown in the last column of the same table. For purposes of comparison, the values of the reflecting power of caesium in contact with glass, as obtained by the polarimetric and spectrophotometric methods are plotted in Fig. 5. It will be noted that the agreement is quite satisfactory for wave-lengths greater than 5500 Å but is not so good for smaller wave-lengths, the deviation becoming more marked the smaller the wave-length. It is true that the observational difficulties are the greatest for the violet end of the spectrum,

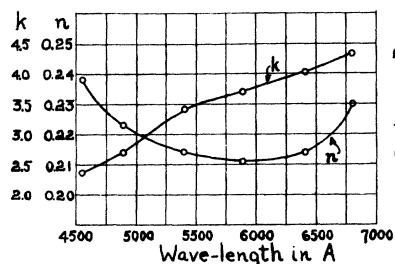


Fig. 4

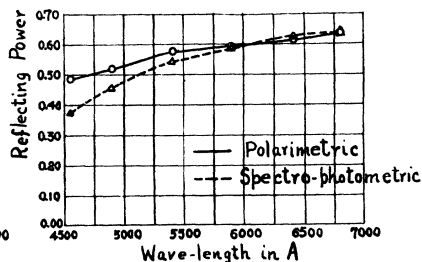
Fig. 4. Coefficient of absorption k and index of refraction n of caesium in contact with glass.

Fig. 5

Fig. 5. Reflecting power of caesium in contact with glass.

but the deviation in the reflecting powers as obtained by the two methods appears in the green part of the spectrum for which the eye is most sensitive. Conroy⁷ found that the direct method yielded values for white light which were several per cent less than the values obtained by the polarimetric method for sodium light. Tate's work⁸ with a glass-silver surface indicates a somewhat similar experience to the one with caesium, though the deviation in the results obtained by Tate were not quite so marked. If there is any discrepancy in the reflecting power as obtained by the two methods, the deviation should become most marked in the ultra-violet.

It is of course desirable to know what the optical constants of caesium would be with respect to air. The customary procedure has been to

⁷ Sir J. C. Conroy, Proc. Roy. Soc. **36**, 196 (1884)

⁸ J. T. Tate, Phys. Rev. **34**, 326 (1912)

assume that the coefficient of absorption remains unaffected by the transparent medium in contact with the metal, but that the index of refraction of the metal with respect to air can be obtained from the index with respect to the medium, by multiplying the latter by the index of refraction of the transparent medium. This procedure has been verified experimentally by a number of investigators.⁹ Further verification has also been made by the writer who determined the optical constants of silver when in contact with air and glass, the method of investigation being the same as that employed in the study of caesium.

These conclusions have been applied to caesium, the constants with respect to air being computed from the mean results given in Table I. The computed values are shown in Table III. The values of k are listed again for convenience. The principle angles of incidence $\bar{\phi}$ and of azimuth $\bar{\psi}$, are given in columns 5 and 6 respectively. The values of ϕ were evaluated graphically by means of Eq. (5)

$$\sin^4 \bar{\phi} \tan^4 \bar{\phi} = n^4(k^2 + 1)^2 + 2n^2(k^2 - 1) \sin^2 \bar{\phi} + \sin^4 \phi. \quad (5)$$

The angle $\bar{\psi}$ was then similarly evaluated from Eq. (6)

$$\tan^2 \bar{\phi} \cos 4\bar{\psi} + 1 = (\tan^2 \bar{\phi} / \tan X) \sin 4\bar{\psi}. \quad (6)$$

TABLE III

Optical constants of caesium with reference to air

λ	n	k	$R(\text{calc.})$	$\bar{\phi}$	$\bar{\psi}$
4550 A	0.362	2.37	0.442	55° 25'	38° 32'
4890	0.339	2.70	0.485	56 13	39 6
5400	0.326	3.41	0.565	58 48	39 43
5890	0.321	3.70	0.594	59 44	39 54
6410	0.326	4.01	0.625	61 8	40 3
6800	0.350	4.34	0.661	63 20	40 6

The reflecting power R is given in the fourth column. The reflection appears to be selective, as the reflecting power for the red end of the spectrum is about fifty per cent greater than that for the violet end. The minimum value of the refractive index obtained for $\lambda 5890$ A seems to be in accordance with the experience of the Duncans² for the element sodium. Their dispersion curve for sodium showed a sharp minimum for $\lambda 5893$. The values of the refractive index for caesium do not change so abruptly.

⁹ W. Voigt, Wied. Ann. **23**, 134 (1884);

P. Drude, Wied. Ann. **39**, 481 (1890);

L. R. Ingersoll and R. T. Birge, Phys. Rev. **29**, 392 (1909);

L. P. Wheeler, Phil. Mag. **22**, 229 (1911).

In order to correlate the optical absorption of the various alkali metals, the values of the coefficients of absorption have been plotted in Fig. 6. The data for the three wave-lengths has been obtained from the work of the Duncans² on sodium and potassium, and from the writer's results on rubidium⁴ and caesium. It is very interesting to note the regularity with which absorption coefficients diminish with atomic number, the values varying inversely as about the three halves or second power of the atomic number. On the other hand the refractive index is found to increase with the atomic number.

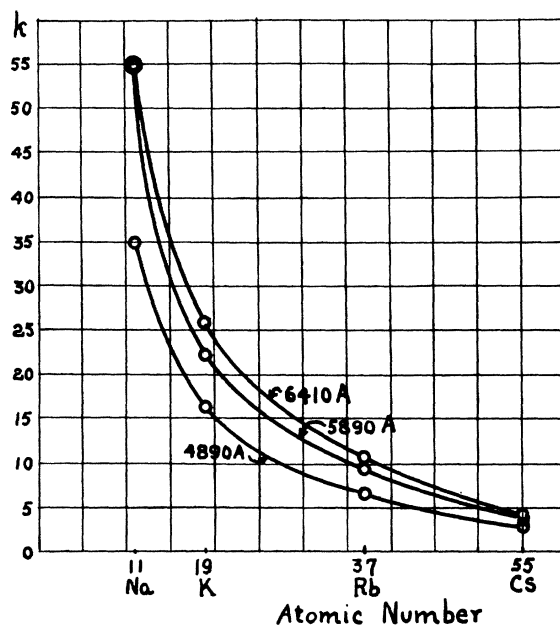


Fig. 6. Variation with atomic number of the coefficients of absorption of the alkali metals.

A computation of the number of free electrons per atom according to Drude's¹⁰ electron theory of metallic dispersion, yields values ranging from 1.5 for $\lambda 6800 \text{ \AA}$ to 2.3 for $\lambda 4550 \text{ \AA}$. As would be expected there is a very large discrepancy between the specific resistance of caesium as determined by electrical methods and as computed from the optical constants, the optical method giving values six to seven times that obtained by electrical methods. Obviously then, until the mechanism of electrical conduction is understood more fully, little can be gained by such computations.

¹⁰ P. Drude, *Ann. der Phys.* **14**, 936 (1904)

It is intended to continue this investigation on caesium in the liquid state so that we might have more experimental information on the relation between optical and electrical properties.

I take this opportunity of expressing my thanks to the Committee on Research of the Carnegie Institute of Technology for funds granted to me for carrying out of this investigation.

CARNEGIE INSTITUTE OF TECHNOLOGY,
PITTSBURGH, PA.
July 31, 1924