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PHYSICAL REVIEW VOLUME 180, NUMBER 1 5 APRIL 1969

Absorption Spectrum of Sr I in the Region of Autoionization from 1646 to 2028 Å

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(Received 23 December 1968)

The atomic absorption cross section of strontium has been measured at an instrumental bandwidth of 0.07 Å in the autoionizing wavelength interval from 1646 to 2028 Å. Corrections have been applied to eliminate the bandwidth dependence of the results. Figures summarizing our best estimate of cross section versus wavelength are presented. The observed structure is grouped into series, and the measured wavelengths and oscillator strengths for the members of each series are tabulated.

I. INTRODUCTION

The absorption spectrum of strontium vapor at wavelengths shorter than its principal series limit at 2177.13 Å was first recorded photographically by Garton, Pery, and Codling in 1959.[1] Absolute absorption cross sections in this autoionizing region were first obtained by two of us (Hudson and Young) in 1963 at an instrumental bandwidth of 1 Å. Shortly thereafter Hudson, Carter, and Stein, using an improved apparatus, were able to obtain absorption spectra of hot gases at an instrumental bandwidth of 0.075 Å.[2] As this approaches the bandwidth used by Garton, Pery, and Codling (0.027 Å), we decided therefore not to publish the 1 Å data, but to wait until high-resolution spectra could be obtained. This paper is an account of these high-resolution spectra.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

Details regarding the basic theory and experimental arrangement have been discussed previously.[3,4] Figure 1 shows the configuration of the apparatus. It consists essentially of a 2.2-m normal incidence scanning monochromator, behind the exit slit of which is a temperature-regulated furnace that serves as an absorption chamber. Light was generated in a hydrogen Hanovia lamp operated at approximately 1000 W. A 1200 lines/mm Bausch and Lomb replica grating was used, which combined with 20-μ entrance

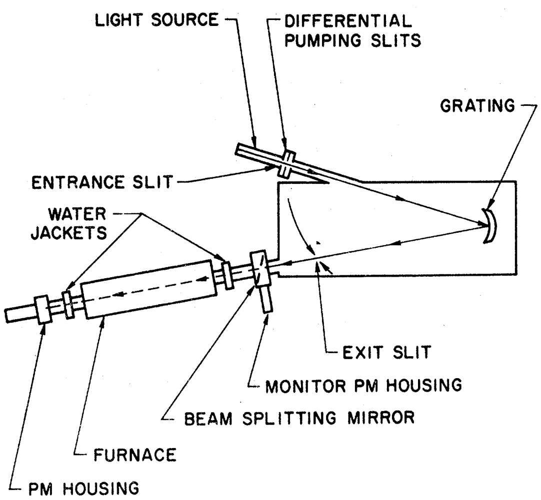

FIG. 1. 2.2-m monochromator and associated equipment.

and exit slits gave a measured instrumental bandwidth of 0.078 Å.

Continuous and simultaneous recordings of incident and transmitted light intensities were obtained over the wavelength interval from 2175 to 1646 Å at five temperature settings in the range from 875 to 950°K (0.055 to 0.338 Torr).

TABLE I. Comparison of recent compilations of thermochemical data for atomic strontium vapor.

Reference	Vapor pressure (mm Hg) 800°K	900°K	1000°K
Hultgren *et al.*[5]	7.31×10^{-3}	1.04×10^{-1}	8.44×10^{-1}
Nesmeyanov[7]	8.35×10^{-3}	1.17×10^{-1}	9.43×10^{-1}
Honig[6]	7.40×10^{-3}	1.00×10^{-1}	$9.9\ \times10^{-1}$

III. VAPOR PRESSURE

Three summaries of thermochemical data have been considered in selecting the vapor-pressure figures for this work. Table I lists the estimated vapor pressure, at the temperatures appropriate to our experiment, obtained from these publications. Hultgren *et al.*[5] and Honig[6] present data which is in good agreement except at the highest temperature, while Nesmeyanov's[7] data is consistently higher by approximately 14%. In plotting the log of the vapor pressure versus the reciprocal of temperature, we find that the data of Hultgren *et al.* closely follow the expected straight line while the points summarized by Honig show wider scatter. We have chosen to calculate the strontium-absorption cross sections using the vapor-pressure data of Hultgren *et al.*; however, the results can be modified to reflect Nesmeyanov's higher vapor-pressure estimate by uniformly lowering the reported cross sections by 14%.

IV. ANALYSIS OF THE DATA

The flux $A_0(\lambda', \Delta\lambda)$, incident on the absorbing vapor, and the transmitted flux $A(\lambda', \Delta\lambda)$, measured by the photomultipliers, are integrated over the monochromator bandwidth $\Delta\lambda$ centered at λ'. These fluxes are related to the atomic-absorption cross section $\sigma_a(\lambda)$ by the relationship

$$A_0(\lambda', \Delta\lambda)/A(\lambda', \Delta\lambda) = \frac{\int_{\lambda'-\Delta\lambda}^{\lambda'+\Delta\lambda} S(\lambda)G(\lambda)d\lambda}{\int_{\lambda'-\Delta\lambda}^{\lambda'+\Delta\lambda} S(\lambda)G(\lambda)\exp[-C_a\sigma_a(\lambda)L]d\lambda}, \quad (1)$$

where $S(\lambda)$ is the flux from the light source incident on the entrance slit, $G(\lambda)$ is the slit function, C_a is the concentration of the absorbing atoms, and L is the path length. For most of the wavelength interval that we have studied, $S(\lambda)$ is a constant over the bandwidth of the monochromator and will cancel from Eq. (1). If, in addition, $\sigma_a(\lambda)$ were constant over the bandwidth, Eq. (1) would reduce to the familiar form

$$A_0(\lambda'; \Delta\lambda)/A(\lambda', \Delta\lambda) = \exp[C_a\sigma_a(\lambda')L], \quad (2)$$

and it would be possible in this straightforward way to obtain the true value of the absorption cross section $\sigma_a(\lambda')$ at the center of the bandwidth, through application of our measured values of $A_0(\lambda', \Delta\lambda)$, $A(\lambda', \Delta\lambda)$, C_a and L. In practice, because of the considerable absorption structure in the region of the strontium autoionization lines, $\sigma_a(\lambda)$ is generally a rapidly varying function within the instrumental bandwidth, and values of the cross section which are averaged across the bandwidth, $\bar{\sigma}(\lambda', \Delta\lambda)$ will result from the solution of Eq. (2). These averaged values can be corrected to yield true cross sections provided, as in this case, the half-widths of the absorption features are greater than the instrumental bandwidth.

A detailed discussion of the integrating effect of a finite spectrograph bandwidth upon absorption features has been presented in an earlier paper.[8] We also presented at that time curves relating the ratio $\bar{\sigma}(\lambda', \Delta\lambda)/\sigma(\lambda')$ to the ratio of bandwidth to linewidth for three cases, (i) at the peak of a Lorentz line, (ii) in the minimum between two Lorentz lines, and (iii) for a cross section varying linearly across the bandwidth. The $G(\lambda)$ in the present work is of the same form as that used to compute the curves in Ref. 8. The final strontium cross sections which we present in this paper were obtained by solving Eq. (2) and subsequently applying the corrections developed

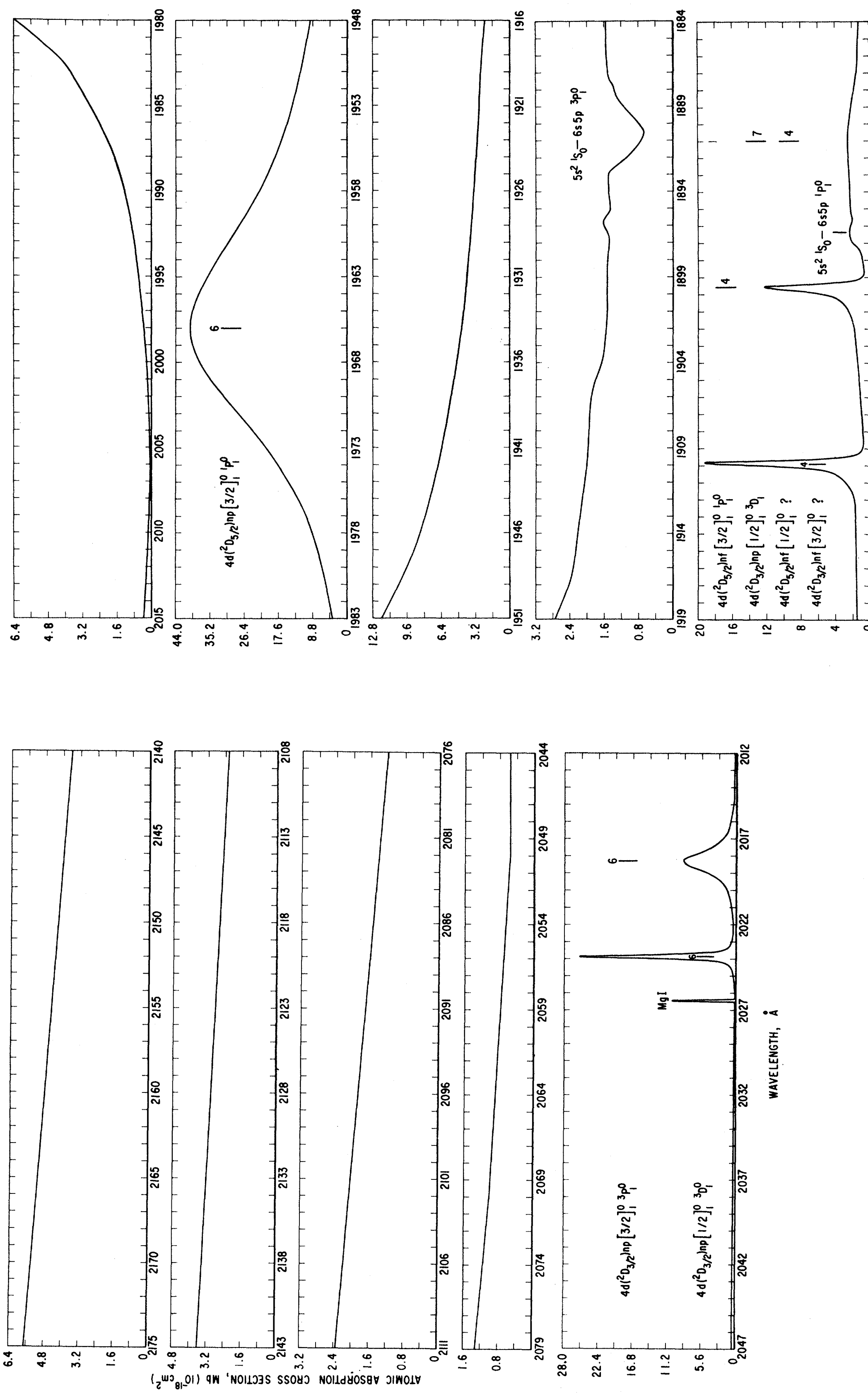

FIG. 2. The atomic absorption cross section of strontium vapor versus wavelength.

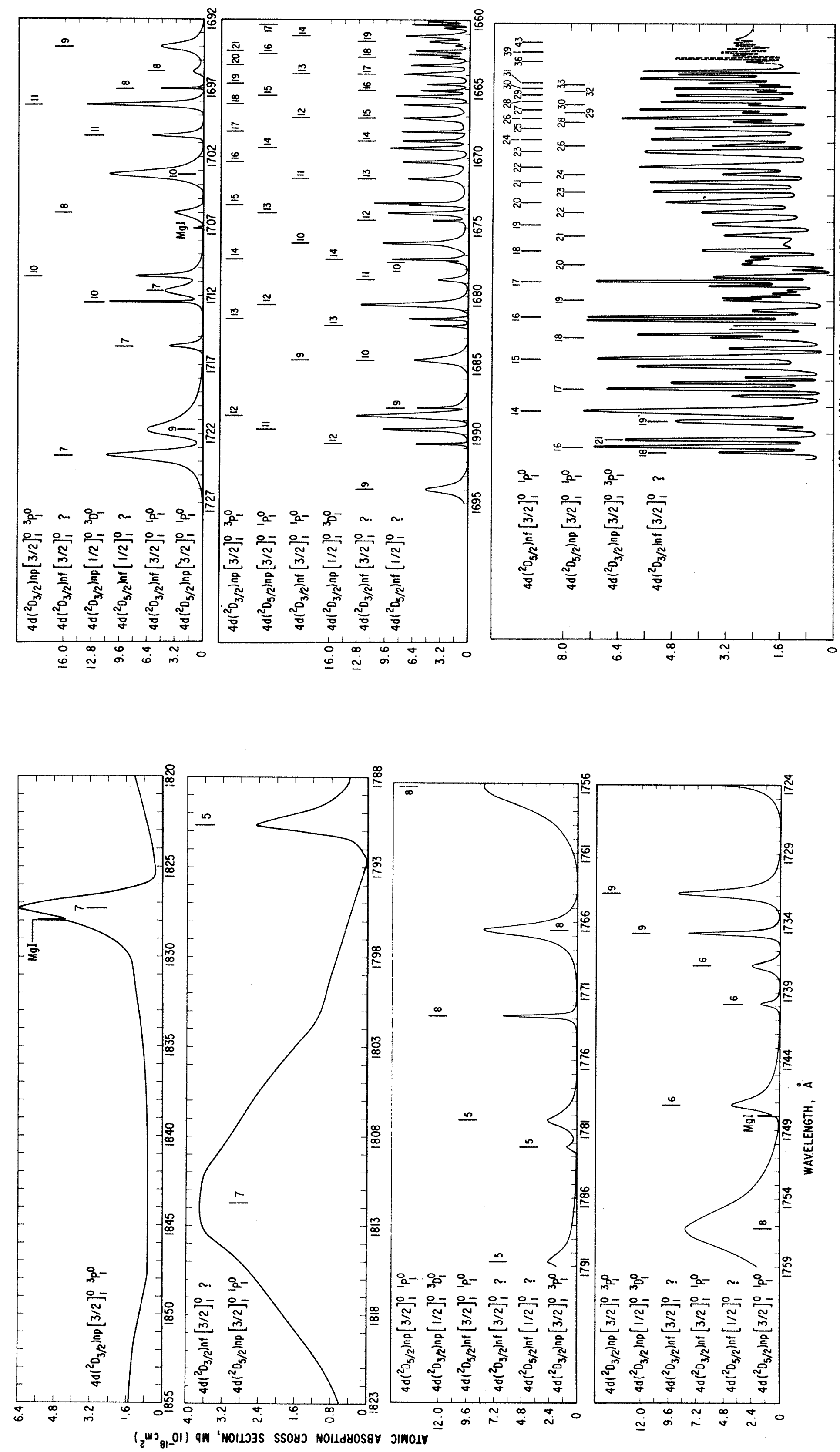

FIG. 2. – *continued*

in Ref. 8 to eliminate the bandwidth dependence of the results. Oscillator strengths were obtained by measuring the area under the curves of corrected cross section versus frequency.

V. RESULTS AND DISCUSSION

In Fig. 2 we show our best estimate of the absorption cross section of strontium vapor between 1646.15 and 2175.00 Å. It was obtained by fitting a smooth curve to the cross sections resulting from the analysis described in Sec. IV. The maximum deviation of the cross sections from this curve is ± 2%. In addition we must assign a systematic error of ± 7%. This estimate does not include the possible error in the vapor pressure discussed in Sec. III. For those lines for which bandwidth dependence corrections had to be made we place an additional uncertainty in the peak values of ± 5%. Below 1648.3 Å the measured linewidths and the distance between successive peaks approached the instrumental bandwidth and corrections could not be made. This portion of the curve, shown as a dashed line in Fig. 2, represents the values of $\bar{\sigma}(\lambda', \Delta\lambda)$ obtained from Eq. (2). The wavelengths were obtained by fitting a dispersion curve to the spectra on the recorder traces using the wavelengths published by Garton and Codling[9] for the sharp absorption lines as our standards. The accuracy of the wavelength scale is estimated to be ± 0.04 Å. A complete listing of cross section versus wavelength is available from the authors.

Tables II through VII present our values of the oscillator strengths of the observed lines. The estimated error on these oscillator strengths is ± 10%, excluding the vapor-pressure error as discussed in Sec. III. We have arranged the lines

TABLE II. Oscillator strengths of transitions in the series Sr I $5s^2\,{}^1S_0-4d({}^2D_{5/2})np\,[\frac{3}{2}]_1^\circ$; $({}^1P_1^\circ)$ limit 60 768.2 cm^{-1}.

n	λ	f
6	1966 ± 4[a]	2.80×10^{-2}
7	1811.74[a]	2.05×10^{-3}
8	1756.22[a]	1.36×10^{-3}
9	1721.71[a]	3.87×10^{-4}
10	1703.20	3.52×10^{-4}
11	1689.62	8.93×10^{-5}
12	1680.60	1.84×10^{-4}
13	1673.95	9.17×10^{-5}
14	1669.28	7.85×10^{-5}
15	1665.52	7.08×10^{-5}
16	1662.50	3.59×10^{-5}
17	1660.31	3.17×10^{-5}
18	1658.36	2.13×10^{-5}
19	1656.95	1.60×10^{-5}
20	1655.57	
21	1654.48	2.83×10^{-5}
22	1653.60	3.03×10^{-5}
23	1652.82	3.14×10^{-5}
24	1652.17	1.99×10^{-5}
25		
26	1651.07[b]	2.06×10^{-5}
27		
28	1650.20[b]	1.50×10^{-5}
29	1649.84[b]	9.77×10^{-6}
30	1649.53[b]	1.40×10^{-5}
31		
32	1649.02[b]	8.02×10^{-6}
33	1648.79[b]	6.63×10^{-6}

[a]New wavelength. [b]New line.

TABLE III. Oscillator strengths of transitions in the series Sr I $5s^2\,{}^1S_0-4d({}^2D_{3/2})np\,[\frac{3}{2}]_1^\circ$; $({}^3P_1^\circ)$ limit 60 487.9 cm^{-1}.

n	λ	f
6	2018.30	5.31×10^{-4}
7	1827.19	9.05×10^{-4}
8	1766.55[a]	4.06×10^{-4}
9	1731.81	3.06×10^{-4}
10	1710.58	1.19×10^{-4}
11	1698.21	1.72×10^{-4}
12	1688.63	1.99×10^{-4}
13	1681.60	3.49×10^{-5}
14	1677.29[b]	5.30×10^{-5}
15	1673.35	5.30×10^{-5}
16	1670.26	8.27×10^{-5}
17	1668.12	4.08×10^{-5}
18	1666.15	5.79×10^{-5}
19	1664.66	3.45×10^{-5}
20	1663.39	6.00×10^{-5}
21	1662.24	3.84×10^{-5}

[a]New wavelength. [b]Double line.

TABLE IV. Oscillator strengths of transitions in the series Sr I $5s^2\,{}^1S_0-4d({}^2D_{3/2})np\,[\frac{1}{2}]_1^\circ$; $({}^3D_1^\circ)$ limit 60 487.9 cm^{-1}.

n	λ	f
6	2023.86	2.51×10^{-4}
7	1859 ± 3[a, b]	
8	1772.79	6.69×10^{-5}
9	1734.71	1.21×10^{-4}
10	1712.44	5.09×10^{-5}
11	1700.44	6.84×10^{-5}
12	1690.68[c]	2.23×10^{-5}
13	1682.12	2.02×10^{-5}
14	1677.29[b]	5.30×10^{-5}

[a]New Line [b]Double line. [c]New wavelength.

TABLE V. Oscillator strengths of transitions in the series Sr I $5s^2\,{}^1S_0$–$4d({}^2D_{5/2})nf\,[\frac{3}{2}]_1^\circ$; $({}^1P_1^\circ)$ limit 60768.2 cm^{-1}.

n	λ	f
4	1867.55	6.73×10^{-4}
5	1780.32	1.25×10^{-4}
6	1737.03	5.98×10^{-5}
7	1711.67	1.44×10^{-4}
8	1695.76	2.65×10^{-5}
9	1684.62[a]	1.52×10^{-4}
10	1676.13	1.57×10^{-4}
11	1671.48[a]	1.22×10^{-4}
12	1667.12[a]	9.42×10^{-5}
13	1663.94[a]	8.37×10^{-5}
14	1661.15	8.13×10^{-5}
15	1659.16	4.39×10^{-5}
16	1657.59	2.93×10^{-5}
17	1656.23	2.93×10^{-5}
18	1655.06	2.34×10^{-5}
19	1654.08	2.77×10^{-5}
20	1653.23	5.02×10^{-5}
21	1652.50	3.66×10^{-5}
22	1651.89	3.94×10^{-5}
23	1651.34	4.60×10^{-5}
24	1650.86[b]	3.28×10^{-5}
25	1650.43[b]	4.29×10^{-5}
26	1650.05[b]	3.59×10^{-5}
27	1649.70[b]	2.90×10^{-5}
28	1649.43[b]	2.76×10^{-5}
29	1649.16[b]	2.48×10^{-5}
30	1648.92[b]	1.88×10^{-5}
31	1648.71[b]	2.13×10^{-5}
36	1647.90[b]	1.95×10^{-5}
39	1647.56[b]	1.29×10^{-5}
43	1647.21[b]	1.43×10^{-5}

[a]Double line. [b]New Line.

TABLE VI. Oscillator strengths of transitions in the series Sr I $5s^2\,{}^1S_0$–$4d({}^2D_{5/2})nf\,[\frac{1}{2}]_1^\circ$; ? limit 60768.2 cm^{-1}.

n	λ	f
4	1859 ± 3[a, b]	
5	1782.29	1.61×10^{-5}
6	1739.82	3.17×10^{-5}
7	1715.65	5.56×10^{-5}
8	1697.03	1.47×10^{-5}
9	1688.09	4.81×10^{-5}
10	1677.45[a]	1.88×10^{-5}

[a]New line. [b]Double line.

TABLE VII. Oscillator strengths of transitions in the series Sr I $5s^2\,{}^1S_0$–$4d({}^2D_{3/2})nf\,[\frac{3}{2}]_1^\circ$; ? limit 60487.9 cm^{-1}.

n	λ	f
4	1877.83	4.99×10^{-4}
5	1790.60	2.98×10^{-4}
6	1747.17	2.12×10^{-4}
7	1723.50	3.96×10^{-4}
8	1705.95	7.60×10^{-5}
9	1693.97	1.66×10^{-4}
10	1684.62[a]	1.52×10^{-4}
11	1678.76	4.88×10^{-5}
12	1674.48	2.23×10^{-5}
13	1671.48	1.22×10^{-4}
14	1668.75	6.14×10^{-5}
15	1667.12[a]	9.42×10^{-5}
16	1665.12	3.63×10^{-5}
17	1663.94[a]	8.37×10^{-5}
18	1662.71	1.57×10^{-5}
19	1661.55	3.59×10^{-5}

[a]Double line.

TABLE VIII. Oscillator strengths of unidentified lines in Sr I.

λ	f
1673.28[a]	9.07×10^{-5}
1661.85[a]	1.15×10^{-5}
1660.58	1.57×10^{-5}
1660.10	2.27×10^{-5}
1659.88	1.15×10^{-5}
1659.46	4.19×10^{-5}
1658.79	1.71×10^{-5}
1658.26[a]	2.44×10^{-5}
1657.71	3.14×10^{-5}
1657.34[a]	1.36×10^{-5}
1656.87[a]	8.02×10^{-6}
1656.79[a]	6.63×10^{-6}
1656.69[a]	6.98×10^{-6}
1656.59[a]	6.28×10^{-6}
1656.38[a]	1.53×10^{-5}
1656.08[a]	1.50×10^{-5}
1655.76[a]	3.84×10^{-6}
1655.51[a]	3.87×10^{-5}
1655.39[a]	
1654.87[a]	1.43×10^{-5}
1648.56[a]	2.69×10^{-5}
1648.39[a]	1.36×10^{-5}
1648.26[a]	2.93×10^{-5}
1647.81[a]	1.47×10^{-5}
1647.68[a]	1.12×10^{-5}
1647.42[a]	1.36×10^{-5}
1647.31[a]	1.15×10^{-5}
Sr I Miscellaneous	
$5s^2\,{}^1S_0$–$6s5p\,{}^3P_1^\circ$	1890 ± 0.4[b] Window
$5s^2\,{}^1S_0$–$6s5p\,{}^1P_1^\circ$	1864.5[b]

[a]New line. [b]New wavelength.

in series following the designations given by Garton and Codling.[9] Unless otherwise stated the wavelengths are those reported by Garton and Codling. No attempt has been made to analyze these lines in terms of Fano resonance profiles as this has recently been done between 2024 and 1722 Å by Garton, Grasdalen, Parkinson, and Reeves,[10] and below 1722 Å the lines are essentially symmetrical. Table VIII presents the wavelengths and oscillator strengths of unidentified and miscellaneous lines observed.

ACKNOWLEDGMENTS

We sincerely thank Dr. R. A. Becker for his help and encouragement in this work and M. E. Brennan and R. Marcoe for their able technical assistance.

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PHYSICAL REVIEW VOLUME 180, NUMBER 1 5 APRIL 1969

Optical Pumping of Neon $^3P_2$ Metastable Atoms

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(Received 23 December 1968)

The $^3P_2$ metastable atoms of neon have been optically oriented. This represents the first case of the optical pumping of non-S state atoms. The optical-pumping process is described, and depolarization cross sections for collisions with ground-state neon and ground-state helium atoms measured. The cross section for collisional depolarization with helium is 4.30 $\pm 0.22 \times 10^{-17}$ cm^2, and with neon is $166 \pm 8 \times 10^{-17}$ cm^2 at 300°K. The metastable $^3P_2$ atoms of Ar and Xe have also been optically pumped. As the polarizability of the noble-gas buffer increases, the collisional depolarization cross section approaches the diffusion cross section.

I. INTRODUCTION

The conventional method of optical pumping introduced by Dehmelt[1] has been applied successfully in the past only to those atoms possessing a ground electronic state of zero angular momentum ($L = 0$). In particular, the optical orientation and detection of atoms has been confined to the alkali atoms ($^2S_{1/2}$),[2,3] Hg($^1S_0$),[4] and He($^3S_1$).[5,6] Engineering difficulties have precluded the optical orientation of other S-state atoms[7] with nonzero spin, while for atoms possessing orbital angular momentum ($L > 0$), it has generally been assumed that considerable depo-