

# VARIATIONAL ENERGIES OF ANOMALOUS STATES OF 2- AND 3-ELECTRON CONFIGURATIONS OF LIGHT ATOMS

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## ABSTRACT

The energy states of the configurations  $2s2p$ ,  $2p^2$ ,  $1s2s2p$ ,  $1s2p^2$ ,  $2s2p^2$ ,  $2p^3$  and  $1s^2 2s^2$  in the atoms from H to F have been calculated by the variational method with simple wave functions. Wherever possible, the energies are the corrected according to the method suggested by Stevenson. These calculated energies have been employed for the identification of the "satellite" lines observed by Edlén and Tyrén in the CV- and CVI-like spectra. The possibility of stable negative ions of H and He in excited states is discussed. The electron affinity of Li atom is reestimated.

Recently Edlén and Tyrén have reported the observation of groups of weak lines to the long wave-length side of the lines  $1s^2 \ ^1S - 1s2p \ ^1P$  in the CV-like spectra, and the  $1s^2 \ S-2p \ ^3P$  in the CVI-like spectra of the light elements. These satellite lines they ascribed to transitions in the respective preceding spectrum with an additional external electron whose effect of screening on the energy of transition giving rise to the main line is small. Thus the transition  $1s^2 \ ^1S-1s2p \ ^1P$  may have as satellites  $1s^2 2s \ ^3S-1s2s2p \ ^3P, ^3P, 1s^2 2p \ ^3P-1s2p^2 \ ^3P, ^3D, ^3S$ , etc., and the line  $1s^2 \ S-2p \ ^3P$  may have as satellites  $1s2s \ ^1S-2s2p \ ^1P, 1s2s \ ^3S-2s2p \ ^3P, 2s2p \ ^3P-2p^2 \ ^3P, 1s2p \ ^1P-2p^2 \ ^1D, ^1S$ , etc. The purpose of this paper is to calculate the energies of the initial states involved in the emission of these satellite lines and to attempt an identification of the lines observed by Edlén and Tyrén.

(1) Edlén and Tyrén, *Nature* 143, 940 (1939).

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The calculations are made with the following simple variational wave functions.

$$1s: R(1s) = \sqrt{4\alpha^3} e^{-\alpha r}$$

$$2s: R(2s) = \left(12\beta^3 (\alpha^2 - \alpha\beta + \beta^2)\right)^{\frac{1}{2}} \left(1 - \frac{\alpha + \beta}{3} r\right) e^{-\beta r}$$

$$2p: R(2p) = \sqrt{4\gamma^5/3} r e^{-\gamma r}$$

The integrals of the kinetic, the electron-nucleus potential, the electron-electron Coulomb and exchange energies can be readily evaluated. They are

$$T(1s) = \alpha^2, \quad T(2s) = \beta^2 \left( \frac{1}{2} + \frac{2\beta^2}{\alpha^2 - \alpha\beta + \beta^2} \right), \quad T(2p) = \gamma^2,$$

$$V(1s) = -2\alpha, \quad V(2s) = -\beta + \frac{(\alpha - 2\beta)\beta^2}{\alpha^2 - \alpha\beta + \beta^2}, \quad V(2p) = -\gamma$$

$$F(1s, 1s) = \frac{5}{4} \alpha,$$

$$F(1s, 2s) = \frac{\alpha\beta}{\alpha + \beta} \left( 1 + \frac{(3\alpha + \beta)\beta^2}{(2 + \beta)^2 (\alpha^2 - \alpha\beta + \beta^2)} \right),$$

$$F(1s, 2p) = \gamma \left( 1 - \frac{x^4}{(1+x)^4} - \frac{2x^4}{(1+x)^5} \right), \quad x = \gamma/\alpha$$

$$F(2s, 2s) = \beta \frac{93 - 244u + 433u^2 - 420u^3 + 245u^4}{128 (1 - u + u^2)}, \quad u = \beta/\alpha$$

$$F(2s, 2p) = \gamma - \frac{\gamma z^4}{(1+z)^4} - \frac{\gamma z^4}{(1-y+y^2)(1+z^2)} \left( 1 - 2y + y^2 + \frac{5(y^2-1)}{1+z} + 5 \left( \frac{1+y}{1+z} \right)^2 \right), \quad y = \frac{\alpha}{\beta}, \quad z = \frac{\gamma}{\beta}$$

$$E_0(2p, 2p) = -\frac{93}{128} \gamma, \quad F_2(2p, 2p) = \frac{9}{5 \times 128} \gamma$$

$$G(1s, 2s) = \frac{8\alpha^3\beta^5}{(\alpha+\beta)^5(\alpha^2+\alpha\beta+\beta^2)}$$

$$G(1s, 2p) = \frac{56\alpha^3\gamma^2}{3(\alpha+\gamma)^7}$$

$$G(1s, 2p) = \frac{4\beta z^5}{(1-y+y^2)(1+z)^7} \left( 14 - \frac{98(1+y)}{3(1+z)} + \frac{185}{9} \left( \frac{1+y}{1+z} \right)^2 \right),$$

$$y = \alpha/\beta, z = \gamma/\beta.$$

The energies of the various states are given by

$$2s2p^3P, E = T(2s) + T(2p) + Z(V(2s) + V(2p)) + F(2s, 2p)$$

$$= G(2s, 2p),$$

$$2p^2 \begin{matrix} 3P \\ 1D \\ 1S \end{matrix}, E = 2T(2p) + 2ZV(2p) + \bar{F}(2p, 2p) \begin{pmatrix} -5F_2(2p, 2p) \\ +F_2(2p, 2p) \\ +10F_2(2p, 2p) \end{pmatrix}$$

$$1s2s2p^4P, E = T(1s) + T(2s) + T(2p) + Z(V(1s) + V(2s) + V(2p)) \\ + F(1s, 2s) + F(1s, 2p) + F(2s, 2p) \\ - G(1s, 2s) - F(1s, 2p) - G(2s, 2p)$$

$$1s2s2p^2P, E = T(1s) + T(2s) + T(2p) + Z(V(1s) + V(2s) + V(2p)) \\ + F(1s, 2s) + F(1s, 2p) + F(2s, 2p) \pm \sqrt{K},$$

$$\text{where } K = |G(1s, 2s)|^2 + |G(1s, 2p)|^2 + |G(2s, 2p)|^2$$

$$- G(1s, 2s)G(1s, 2p) - G(1s, 2s)G(2s, 2p) -$$

$$- G(1s, 2p)G(2s, 2p),$$

$$1s2p^3 \begin{matrix} 3P \\ 2P \\ 2D \\ 2S \end{matrix}, E = L \begin{pmatrix} -5F_2(2p, 2p) - 2G(1s, 2p) \\ -5F_2(2p, 2p) + G(1s, 2p) \\ +F_2(2p, 2p) - G(1s, 2p) \\ +10F_2(2p, 2p) - G(1s, 2p) \end{pmatrix},$$

$$\text{where } L = T(1s) + 2T(2p) + Z(V(1s) + 2V(2p)) + 2F(1s, 2p)$$

$$+ 4F_0(2p, 2p);$$

$2s2p^2 \begin{Bmatrix} {}^4P \\ {}^2P \\ {}^2D \\ {}^2S \end{Bmatrix}$  similar to the corresponding expressions for  $1s2p^2$ , with  $2s$  replacing  $1s$  throughout.

$$2p^3 \begin{Bmatrix} {}^4S \\ {}^2D \\ {}^2P \end{Bmatrix} E = 3T(2p) + 9ZV(2p) - 3F_0(2p, 2p) \begin{Bmatrix} -15F_2(2p, 2p) \\ -6F_2(2p, 2p) \\ +0 \end{Bmatrix}$$

In the calculation of the energy of  $2s2p^2 {}^4P$  the parameter  $\alpha$  is so chosen that the wave function of the state  $2s2p^2 {}^4P$  is orthogonal to that of  $1s2p^2 {}^4P$ , i.e.,  $\alpha$  is given the value determined for the  $1s$  wave function of  $1s2p^2 {}^4P$ . Although the wave function of  $1s2p^2 {}^4P$  determined by the simple variational calculation is not exact, the closeness between the energy of  $1s2p^2 {}^4P$  calculated and the observed value indicates that the wave function is quite good. It is thought that the orthogonalization of  $2s2p^2 {}^4P$  to this  $1s2p^2 {}^4P$  wave function is sufficiently accurate for these calculations. Similarly, in the calculation of the  $2s2p^2 {}^2P$  state, the parameter  $\alpha$  is given the value determined for the  $1s2p^2 {}^4P$  state so that the  $2s2p^2 {}^4P$  wave function is orthogonal to that of  $1s2p^2 {}^4P$ . No difficulty is encountered with the state  $1s2p2p^2 {}^4P$  since there is no quartet state below  $1s2s2p^2 {}^4P$ . As the numerical work would be considerable if all the three parameters  $\alpha, \beta, \gamma$  are subject to variations, we give  $\alpha$  the value equal to the atomic number  $Z$  since the screening of  $1s$  by the  $2s, 2p$  electrons is negligible as is seen from the calculations for  $1s2p^2$ . In the calculation for the various states of  $2p^2$  and  $2p^3$ , the parameter  $\gamma$  is varied separately for the various states. For the other configurations, the parameters are varied only for the lowest state; the other states are calculated with these parameters so determined. The result of these calculations are given in the following tables.

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(2) Of Morse, Young and Haurwitz, *PhDs. Rev.* 48, 948 (1935).

	H <sup>-</sup>	He	Li <sup>+</sup>	Be <sup>2+</sup>	B <sup>3+</sup>	C <sup>4+</sup>	N <sup>5+</sup>	O <sup>6+</sup>
2s2p <sup>3</sup> P	0.2704	1.5042	3.7733	7.0206	11.2681	16.5157	22.7627	30.0117
<sup>1</sup> P			3.4213	6.5606	10.6931	15.8217	21.9575	29.0867
$\alpha$	1.0	1.99	2.978	3.973	4.968	5.968	6.968	7.963
$\beta$	.39	.91	1.41	1.91	2.41	2.91	3.41	3.91
$\gamma$	.34	.86	1.36	1.86	2.36	2.87	3.37	3.88
2p <sup>2</sup> <sup>3</sup> P	0.2260	1.3976	3.5896	6.7412	10.9142	16.0875	22.2577	29.4289
<sup>1</sup> D	0.1985	1.3279	3.4577	6.5873	10.7171	15.8468	21.9761	29.1057
<sup>1</sup> S	0.1604	1.2268	3.2933	6.3695	10.4261	15.4924	21.6587	28.6251
$\alpha$	.336	.958	1.336	1.836	2.336	2.836	3.336	3.836
$\beta$	.315	.815	1.315	1.815	2.315	2.815	3.315	3.815
$\gamma$	.283	.784	1.283	1.783	2.283	2.783	3.283	3.783

Table I. Variational wave functions and energies of 2s2p <sup>3</sup>P, <sup>1</sup>P and 2p<sup>2</sup> <sup>3</sup>P, <sup>1</sup>D, <sup>1</sup>S.

The energies of 2p<sup>2</sup> <sup>3</sup>P, <sup>1</sup>D, <sup>1</sup>S are to be corrected by adding respectively the corrections 0.0098, 0.0099 and 0.0430. See text below.

	He <sup>-</sup>	Li	Be <sup>+</sup>	B <sup>2+</sup>	C <sup>3+</sup>	N <sup>4+</sup>	O <sup>5+</sup>	F <sup>6+</sup>
1s2s2p <sup>4</sup> P	4.8260	10.698	20.089	32.492	47.894	66.296	87.700	112.102
<sup>2</sup> P		10.599	19.892	32.176	47.478	65.759	87.044	111.331
<sup>2</sup> P		10.378	19.590	31.827	47.073	65.310	86.560	110.810
$\alpha$	2	3	4	5	6	7	8	9
$\beta$	0.59	1.11	1.64	2.15	2.65	3.15	3.64	4.14
$\gamma$	0.83	0.877	1.41	1.925	2.43	2.96	3.49	3.99
1s2p <sup>2</sup> <sup>4</sup> P	4.2311	10.4463	19.6904	31.9465	46.2070	65.469	86.735	111.006
<sup>2</sup> P		10.332	19.5538	31.695	46.852	65.015	86.179	110.343
<sup>2</sup> D		10.349	19.520	31.700	46.883	65.067	86.258	110.440
<sup>2</sup> S		10.237	19.341	31.355	46.674	64.695	85.820	109.942
$\alpha$	1.997	2.975	3.958	4.946	5.937	6.931	6.927	8.923
$\gamma$	0.840	0.893	1.416	1.934	2.446	2.954	3.456	3.962

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$2s2p^3\ ^4P$	1.3612	4.4816	8.8963	14.8137	22.2200	31.1436	41.5604	53.4750
$^2P$		3.8896	8.090	13.791	20.996	29.665	39.905	51.609
$^2D$		4.182	8.484	14.287	21.591	30.379	40.694	52.513
$^2S$		4.030	8.269	14.007	21.249	29.972	40.223	52.002
$\alpha$	1.997	2.975	3.958	4.946	5.937	6.931	7.927	8.923
$\beta$	0.82	1.32	1.81	2.31	2.81	3.30	3.78	4.27
$\gamma$	0.71	1.207	1.703	2.206	2.711	3.217	3.723	4.225

$2p^3\ ^4S$	4.1199	8.3856	14.1508	21.4164	30.1827	40.4472	52.2137
$^2D$	3.9728	8.1751	13.8777	21.0810	29.7823	39.9842	51.6865
$^2P$	3.8764	8.0367	13.6970	20.8575	29.5170	39.6767	51.3369
$\gamma(^4S)$	1.172	1.672	2.172	2.672	3.172	3.672	4.172
$\gamma(^2D)$	1.152	1.652	2.152	2.652	3.152	3.652	4.152
$\gamma(^2P)$	1.137	1.637	2.137	2.637	3.137	3.637	4.137

Table 2. Variational wave functions and energies

	Li	Be	B	C	N	O	F
$1s^2 2s^2\ ^1S$	14.7872	29.0597	48.3785	72.7180	102.060	136.410	175.795
corrected	14.8468	29.1199	48.4413	72.7807	102.119	136.469	175.858
observed		29.333	48.694	73.069	102.446	136.832	176.223
$\alpha$	2.690	3.706	4.714	5.717	6.718	7.718	8.718
$\beta$	0.592	1.167	1.707	2.235	2.754	3.268	3.789

Table 3. Variational wave functions and energies of  $1s^2 2s^2\ ^1S$ .  
The corrected values are those corrected by Stevenson's method.  
See text below.

## IMPROVEMENT OF VARIATIONAL ENERGIE

On a comparison between the observed energies and those calculated by means of simple wave functions of the type (1), it is found that the deviations are greatest whenever there are equivalent

electrons, such as  $1s^2$ ,  $2s^2$ , etc.<sup>2</sup> For configurations such as  $1s2s$  and  $1s2p$ , the calculated energies can be very close to the observed values. This is undoubtedly due to the fact that for equivalent electrons whose interactions are greatest on account of the great overlap of their wave functions, the simple wave functions of the type (1) do not take sufficiently good account of their interactions. Somewhat better results can be obtained by the use of more complicated forms for the single-electron wave functions, as we shall demonstrate below for the normal state  $1s^2\ ^1S$  of He. But an upper limit to the accuracy that can be attained by the use of single-electron wave functions is set by the self-consistent field method of Hartree and Fock. It was shown by Hylleraas that considerable improvement over the self-consistent field result can be obtained by introducing the distance  $r_{12}$  between the two electrons into the wave functions.<sup>3</sup> Unfortunately, the method of Hylleraas can be applied only to configurations with  $s$  electrons; even then the amount of labor involved in the calculation of a three electron configuration such as  $1s^2\ 2s$  is prohibitive. Hence the method of Hartree-Fock will probably remain to be the method for obtaining the best possible wave functions, and in their absence calculations with the simple wave functions of the type (1) will be useful for certain purposes on account of the comparatively small amount of labor involved.

One way to obtain better energy values than those given by the use of wave functions of the type (1) is to employ slightly more complicated trial wave functions. To illustrate this, consider the normal state of He. The wave function (1) leads to the energy  $-5.695\ R_h$  as is well known. With the wave function

$$\psi(1s) = A(e^{-\alpha r} + a e^{-\beta r}) \quad (2)$$

where  $\alpha$ ,  $\beta$  and  $a$  are subject to variations, we find  $E(1s^2\ ^1S) = -5.725\ R_h$ , with  $a=2$ ,  $\alpha=3.205$  and  $\beta=1.442$ . This value lies between

(3) Hylleraas, *Zells. f. Physik* 48, 469 (1928); 54, 347 (1929).

ween the value  $-5.695$  and the value  $-5.75$  obtained by the method of Hartree<sup>4</sup>. For other configurations than  $1s^2$ , however, the use of such wave functions will increase the amount of computation enormously.

Stevenson<sup>5</sup> has suggested a method for improving the energies of systems with two electrons outside a closed shell, as given by the Hartree-Fock method. The method consists in using for the wave function of the system

$$\Psi = \Psi_0 X(\cos\vartheta)$$

where  $\Psi_0$  is the correct combination of single-electron wave functions determined already by the method of Hartree-Fock, and  $\vartheta$  is the angle between the radius vectors of the two valence electrons. On setting  $X(\xi) = \sum a_n \xi^n$  where  $\xi = \cos\vartheta$ , the variational principle applied to  $\Psi$  leads to a secular equation for the energy correction  $\Delta E$ . For  $1s^2$  S of He, this comes out to be  $\Delta E = -0.023 Rh$  and brings the self-consistent field value for the energy to  $-5.773 Rh$ .

We shall now apply this method to the energy states of  $2p^2$ . Instead of the Hartree-Fock wave functions which are not available, we shall employ our variational wave functions. This is justified since we are evaluating some corrections that are small. In his notation, we find

$$F_1 = \frac{5 \times 37}{3 \times 253} \gamma, \quad F_3 = \frac{35}{256} \gamma, \quad A = \frac{1}{3} \gamma^2,$$

$$2p^2 \text{ } ^3P: H_{01} = \frac{1}{5} F_1 - \frac{3}{35} F_3, \quad H_{11} = \frac{4}{5} A, \quad N_{11} = \frac{11}{5},$$

$$(\Delta E)^2 - 4 A (\Delta E) - 5 H_{01}^2 = 0;$$

(4) Quoted in Pauling and Wilson, "Introduction to Quantum Mechanics" New York, (1935), p. 224.

(5) Stevenson, A. F., *Phys. Rev.* 56, 566 (1939).



$$2p^2 \ ^1D: H_{01} = \frac{7}{75} F_1 + \frac{3}{275} F_2, \quad H'_{11} = \frac{28}{75} A, \quad N_{11} = \frac{7}{75},$$

$$(\Delta E)^2 - 4A(\Delta E) - \frac{75}{7} H_{01}^2 = 0,$$

$$2p^2 \ ^1S: H_{01} = \frac{4}{15} F_1 + \frac{6}{35} F_2, \quad H'_{11} = \frac{16}{15} A, \quad N_{11} = \frac{4}{15},$$

$$(\Delta E)^2 - 4A(\Delta E) - \frac{15}{4} H_{01}^2 = 0.$$

For values of the parameter  $\gamma$  not very small compared with one as is with our case, the corrections are independent of  $\gamma$  and are

$$\Delta E(^1P) = -0.0049, \quad \Delta E(^1D) = -0.00495, \quad \Delta E(^1S) = -0.0216$$

in units of  $2Rh$ , or

$$\Delta E(^1P) = -0.0098, \quad \Delta E(^1D) = -0.0099, \quad \Delta E(^1S) = -0.0432$$

in units of  $Rh$ . The energies given in Table I are to be corrected by these amounts, although the corrections are probably small compared with the actual deviations of the calculated energies from the true values.

In an earlier paper, Wu has attempted an estimate of the electron affinity of Li by calculating the energy of the state  $1s^2 2s^2 \ ^1S$  in the series  $Li^-, Be, B^+, C^{++}$  and extrapolating to Li the "correction" found on comparing the observed and the calculated energies for the Be,  $B^+$ ,  $C^{++}$ . Now for the configuration  $1s^2 2s^2 \ ^1S$ , it is possible to extend Stevenson's method to apply first to the  $2s$  electrons in the field of the two  $1s$  electrons, and then to the  $1s$  electrons regarded as moving in the field of the two  $2s$  electrons. Using our variational wave functions, we find, again in Stevenson's notation,

$$\text{For } \Delta E(1s^2), \quad A \equiv 2\alpha^2, \quad F_0 = \frac{3}{8}\alpha, \quad F_2 = \frac{3}{8}\alpha, \quad F_4 = 0.2605\alpha,$$

$$(\Delta E)^2 - (2A + \frac{2}{5}F_2)(\Delta E) - \frac{1}{5}(F_1)^2 = 0, \quad (3)$$

For  $\Delta E(2s^2)$ ,  $A = \frac{6\beta^4}{\alpha^2 - \alpha\beta + \beta^2} (1 - \gamma + \frac{1}{2}\gamma^2)$ ,  $\gamma = \frac{\alpha + \beta}{3\beta}$

$$F_1(2s, 2s) = \frac{27\beta^6}{8(\alpha^2 - \alpha\beta + \beta^2)^2} (1 - 5\gamma + 11\gamma^2 - 49\gamma^3 + \frac{185}{32}\gamma^4),$$

$$(\Delta E)^2 = 2A(\Delta E) - \frac{1}{2}(F_1)^2 = 0. \quad (4)$$

For  $\alpha$  greater than 1, the correction  $\Delta E(1s^2)$  is practically independent of  $\alpha$  and (3) gives

$$\Delta E(1s^2) = -0.0115(2Rh) = -0.0230 Rh.$$

For  $\Delta E(2s^2)$ , calculations with the variational parameters in Table 3 give

$$\begin{array}{ccccccc} \text{Li}^- & \text{Be}^- & \text{B}^+ & \text{C}^{++} & \text{N}^{++} & \text{O}^{++} & \text{F}^{++} \\ \Delta E(2s^2) & -0.0366, & -0.0372, & -0.0398, & -0.0397, & -0.0353, & -0.0348, & -0.0400 \end{array}$$

in units of  $Rh$ . The calculated energies of  $1s^2 2s^2$   $1S$  corrected for both  $\Delta E(1s^2)$  and  $\Delta E(2s^2)$  are given in the second row in Table 3. An extrapolation of the "correction" to  $\text{Li}^-$  leads to an expected value for the energy of  $1s^2 2s^2$   $1S$  of  $\text{Li}^-$  of  $-15.020 Rh$ . This would lead to an electron affinity of about 0.9 volt for the  $\text{Li}$  atom.

#### NEGATIVE IONS OF H AND He IN EXCITED STATES

From Table 1, it is seen that the energy of  $2s 2p$   $^3P$  of  $\text{H}^-$  is  $-0.2701 Rh$  which is lower than the state  $n=2$  of  $\text{H}$  by about 0.27 volt. This means that the  $\text{H}$  atom in the state  $n=2$  has an electron affinity of 0.27 volt. The state  $2s 2p$   $^3P$  is, however, subject to autoionization and has probably a lifetime of the order  $10^{-8}$  second<sup>7</sup>.

(6) Wu, Ta-You, *Phil. Mag.* 22, 837 (1936)

(7) On the basis of calculations of the probabilities of autoionization of similar states in doubly excited  $\text{He}$ . See paper "Autoionization in Doubly Excited Helium and the  $\lambda 320$  and  $\lambda 357$  Lines" by Ta-You Wu appearing elsewhere.

The state  $2p^2\ ^3P$  of  $H^-$  is about  $0.0142\ R_h$  or  $0.19$  volt above the state  $n=2$  of  $H$ , according to the corrected energy values in Table 1. With the following wave function for the  $2p$  electron

$$R(2p) = \sqrt{\frac{4\gamma^6}{3}} \left[ 1 + \frac{64a}{(1+x)^5} + \frac{a^2}{x^5} \right]^{-\frac{1}{2}} r (e^{-\gamma r} + ae^{-\delta r}), \quad x = \delta/\gamma$$

we find after some calculations the value  $-0.2315\ R_h$  for the energy of  $2p^2\ ^3P$  of  $H^-$ , the variational parameters being  $\gamma = 0.4985$ ,  $x = 0.5$ , and  $a = 0.3$ . When the same correction by Stevenson's method is applied, the energy of  $2p^2\ ^3P$  of  $H^-$  becomes  $-0.2414\ R_h$  which is only  $0.0086\ R_h$  or  $0.15$  volt above the state  $n=2$  of  $H$ . It is thought probable that when better wave functions such as Hylleraas' are available that take more proper account of the interactions between the two  $2p$  electrons, the energy of  $2p^2\ ^3P$  in  $H^-$  may come out to be lower than the state  $n=2$  of  $H$ . In that case, the state  $2p^2\ ^3P$  will not be subject to autoionization, and as radiative transition to the normal state  $1s^2\ ^1S$  of  $H^-$  is forbidden, a long-lived negative ion of  $H$  in an excited state will be possible.

For  $He$ , it is seen from Table 2 that there are many stationary states in  $He^-$  which are however subject to autoionization. The lowest one,  $1s\ 2s\ 2p\ ^4P$ , lies about  $0.021\ R_h$  or  $0.32$  volt above the  $1s\ 2s\ ^3S$  of  $He$  according to these calculations and is hence in a position to undergo autoionization. It is however possible that the actual energy of  $1s\ 2s\ 2p\ ^4P$  is lower than  $1s\ 2s\ ^3S$  of  $He$ . In that case the state  $1s\ 2s\ 2p\ ^4P$  will not be subject to autoionization and a stable negative ion of  $He$  will be possible. This may account for the observation of Hiby who claimed to have found  $He^-$  in the mass-spectrograph<sup>8</sup>, since the configuration  $1s^2\ 2s\ ^3S$  of  $He^-$  has been found to be unstable<sup>9</sup>.

#### IDENTIFICATION OF SATELLITE LINES IN CVI

With the energies given in the above tables and those of Morse, Young and Haurwitz<sup>2</sup>, it has been shown in an earlier paper<sup>9</sup> that

(8) Hiby, *N. W., Ann der Physik* **34**, 478 (1939).

(9) Wu, Ta-You, *Phys. Rev.* **58**, 1114 (1940).

the calculated positions of the transitions  $1s^2 2s^2 S - 1s 2s 2p^2 P$ ,  $^2P$ ,  $1s^2 2p^2 P - 1s 2p^2 S$ ,  $^2P$ ,  $^2D$  in CV agree very well with the satellite lines observed by Edlen and Tyren in the neighborhood of the transition  $1s^2 \ ^1S - 1s 2p \ ^1P$  in CVI. A discussion of the effect of autoionization on the width of these lines is given elsewhere<sup>7</sup>.