MEASUREMENTS OF WAVE LENGTHS IN THE SPECTRUM OF NEON

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CONTENTS

I. INTRODUCTION

For several years past the Bureau of Standards has made use of the neon spectrum in various researches with the Fabry and Perot interferometer. As a result a considerable number of direct comparisons of neon wave lengths with the primary cadmium standard, as well as a large number of relative determinations of neon wave lengths, have accumulated. Although much additional work on the neon spectrum as a whole is desirable, our results with the interferometer are fairly definitive for the wave lengths of 55 of the stronger lines, and it is thought advisable to publish these without further delay.

Wave-length measurements in the spectrum of neon are of special interest and importance for several reasons. The ordinary or primary spectrum of neon consists, roughly, of three groups of strong lines in addition to a larger number of more or less evenly distributed faint lines. Two of these groups of strong lines lie in the ultra-violet, one between 2900 A and 3100 A, and the other between 3300 A and 3700 A. The third group lies in the visible yellow and red between 5800 A and 7500 A. This group contains more than 30 strong lines whose intensities are much greater than those of lines in the other two groups. The great strength of these lines gives the neon spectrum importance as a source of standard wave-lengths. The radiations are quite homogeneous and the wave lengths can therefore be measured with considerable accuracy by means of the interferometer. These radiations are so homogeneous that they produce interference fringes even when the retardation or path difference of the interfering beams exceeds 300 000 waves.[1]

The great accuracy in wave-length determinations, to which these radiations are susceptible, adds interest to the subject of regularities in the spectrum of neon. Watson[2] was the first to observe that most of the strong lines in the neon spectrum could be placed in groups of three or four whose frequency differences seemed to be constant. Accurate measurements of wave lengths permit a test of the actual constancy of these frequency differences and bring out a remarkable set of spectral regularities.

The first neon wave-length measurements by means of an interferometer were made by Priest,[3] who compared the wave length 5852 A with the fundamental spectroscopic standard, the red radiation of cadmium 6438 A. Later he[4] determined the values of 9 other neon wave lengths relative to that of the yellow line 5852 A of neon. Other determinations relative to Priest's value of 5852 A were made by Meggers[5] and by Perard.[6] A direct comparison of the neon line 6402 A with the cadmium line 6438 A was made by Takamine.[7] Further measurements were made by Meissner[8] but it has been impossible for us to obtain a copy of the publication in which the details of this work appear. Some of Meissner's results are given in another paper,[9] in which frequency differences are discussed.

II. APPARATUS

Two fused quartz tubes containing neon gas at a pressure equivalent to that of several millimeters of mercury were used in these investigations. One of the tubes has been described elsewhere in this Bulletin.[10] This identical tube has done much service during the past three years and is still in excellent condition.

The cadmium tubes were of the H type used by Michelson and others. A few of these tubes were made of fused quartz and the remainder were made of glass. They contained a few milligrams of metallic cadmium which was vaporized when the tubes were heated to 320° C in a small brass oven.

Both neon and cadmium tubes were caused to emit light by passing a high-tension alternating current through them. The

[1] Fabry and Buisson, Jour. de Phys., (5), 2 p. 442; 1912.

[2] Watson, Astroph. Jl., 33, p. 399; 1911.

[3] Priest, this Bulletin, 6, p. 573; 1911.

[4] Ibid., 8, p. 539; 1912.

[5] Meggers, this Bulletin, 12, p. 202; 1915.

[6] Perard, Comptes Rendus 154, p. 1798; 1912.

[7] Takamine, Proc. Tokio Math.-Phys. Soc., (2) 8, p. 9; 1915.

[8] Meissner, Ann. d. Phys., 51, p. 115; 1916.

[9] Meissner, Phys. Zeitschr., 17, p. 549; 1916.

[10] This Bulletin, 12, p. 202; 1915.

60-cycle commercial current was transformed from 110 volts to about 10 000 volts. From 0.5 to 3.0 amperes was used on the primary causing about 3 to 20 milliamperes to pass through the tubes.

The Fabry and Perot type of interferometer, consisting of two partially reflecting plane surfaces held a few millimeters apart and exactly parallel by an invar separator or etalon, was used for all of our interferometer measurements of wave lengths. Each radiation of the neon light passing through the interferometer formed circular fringes which were brought to a focus in the same plane by an achromatic lens. In order to separate these superposed images, they were projected on the slit of a prism or grating spectrograph, portions of them accordingly being photographed as transverse bars across the spectral lines. The instruments employed have already been described in this Bulletin.[11]

III. MEASUREMENT OF WAVE LENGTHS IN THE SPECTRUM OF NEON

1. INTERFEROMETER MEASUREMENTS

The neon wave lengths which were measured with the aid of interferometers are given in Table 1. This table contains the results of six different sets of wave-length comparisons. The first three sets comprise measurements of neon wave lengths in terms of the cadmium standard $\lambda = 6438.4696$ A, and the last three sets represent determinations of neon wave lengths relative to each other. Each set of measurements will be referred to by column number in the following summary of important particulars relating to each:

Column 1 represents a large number of neon waves whose lengths were measured directly in terms of the fundamental standard $\lambda = 6438.4696$ A. The interferometer plates used for these measurements were the identical nickeled quartz plates used by Fabry and Buisson [12] in their measurement of secondary standards in the spectrum of the iron arc, and were also used by Burns [13] for the same purpose. Separations of 2, 7.5, 10, 15, 20, and 25 mm were used for the interferometer plates in this work on the neon spectrum.

The results in column 2 were obtained with interferometers having quartz plates with thin nickel films and those in column 3

[11] This Bulletin, 13, p. 245, 1916; and 14, p. 159, 1917.
[12] Fabry and Buisson, Astroph. Jl., 28, p. 169; 1908.
[13] Burns, this Bulletin, 12, p. 179; 1915.

were derived from interferometers whose plates were of glass covered with thin copper films. These plates and films were the same ones used by Merrill[14] in measurements of wave lengths in the helium spectrum. Etalons of 5, 10, 25, and 40 mm were used for column 2 and the same etalons were again used for column 3.

For column 1, the practice was to take photographs of the neon spectrum both before and after an exposure to the cadmium spectrum. The interferometers were used at room temperatures and in many cases slight changes in the etalons were shown by small differences in the diameters of the fringes photographed in the first and last exposures. The mean of both neon measurements was compared with the cadmium measurements and it was hoped that the effect of changes in the interferometer would be eliminated by this procedure. In columns 2 and 3 the neon and cadmium spectra were photographed simultaneously upon the same plate to avoid the difficulty of temperature changes in the interferometer.

Column 4 contains measurements of neon wave lengths originally made in terms of Priest's value for the yellow neon line, viz, 5852.4862 A. This work was done with the same plates and films used for the measurements in column 1, and was in fact undertaken to determine the phase change correction of these films for Burns's determinations of secondary standards in the iron spectrum mentioned above. The values given in column 4 were recalculated in terms of 5852.488 A as the standard.

The neon spectrum was recently made use of at this Bureau in some work on the refractive index of air, and the relative wave-length determinations in column 5 are incidental to this work. For the wave-length reductions the values 6096.1629 A, 6334.4280 A, 6929.4677 A, and 7032.4129 A were assumed as standards and the correction for dispersion of phase change at reflection was avoided by using differences of large and small orders of interference, as explained elsewhere in this Bulletin.[15] The four assumed standards above, and those mentioned later, are derived by taking the weighted means of columns 2 and 3 in Table 1. Etalons of 3.75, 7.5, and 25 mm were used. The relative phase change corrections for the other five columns were actually computed from wave-length measurements with large and small interferometers, as previously described.[16]

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[14] Merrill, this Bulletin, 14, p. 159; 1917.

[15] This Bulletin, 14, p. 163; 1917.

[16] This Bulletin, 13, p. 245; 1916.

The values for red and infra-red lines contained in column 6 were determined relative to the following values assumed as standards:

6506.5281
6532.8826
6598.9528
6678.2762
6717.0428

The glass plates with copper films which were used for 3 and 5, were also used for 6. Separations of 3, 10, and 25 mm were used in the interferometers.

TABLE 1.—Interferometer Measurements of Wave Lengths in the Neon Spectrum

I	λ Adopted	1	2	3	4	5	6	Meissner	Priest
5	3369.904	904	....	....	904	....	....	....	....
6	3417.906	9059	....	....	907	....	....	....	....
6	3447.705	7053	....	....	707	....	....	....	....
6	3454.197	1970	....	....	199	....	....	....	....
5	3460.526	526	....	....	534	....	....	....	....
4	3464.340	340	....	....	....	....	....	....	....
5	3466.581	5814	....	....	588	....	....	....	....
6	3472.578	5783	....	....	574	....	....	....	....
4	3498.067	0668	....	....	....	....	....	....	....
4	3501.218	2182	....	....	221	....	....	....	....
5	3515.192	1921	....	....	197	....	....	....	....
8	3520.474	4737	....	....	475	....	....	....	....
4	3593.526	526	....	....	....	....	....	....	....
4	3593.634	634	....	....	....	....	....	....	....
5	3600.170	170	....	....	....	....	....	....	....
5	3633.664	664	....	....	....	....	....	....	....
8	5330.779	779	....	....	....	....	....	....	....
7	5341.096	096	....	....	....	....	....	....	....
6	5400.562	5620	....	....	....	....	....	....	....
4	5764.419	419	....	....	....	....	....	....	....
2	5820.155	155	....	....	....	....	....	....	....
10	5852.488	4879	4885	4877	488	4882	....	488	4862
6	5881.895	8952	8960	8951	895	....	....	896	8958
8	5944.834	8344	8347	8339	835	8340	....	834	8344
4	5975.534	5345	....	5333	534	....	....	534	....
4	6029.997	9972	....	9969	....	....	....	999	....
7	6074.338	3372	3384	3374	337	3387	....	337	3383
8	6096.163	1629	1634	1627	161	1630	....	163	1608
9	6143.062	0618	0632	0621	063	0626	....	061	0600
5	6163.594	5944	596	5929	....	....	....	594	....
4	6217.280	2818	280	2804	280	....	....	279	....
7	6266.495	4951	4950	4949	496	4964	....	495	4948
4	6304.789	7888	790	7890	789	....	....	788	7929
8	6334.428	4279	4280	4282	....	4280	....	428	....
8	6382.991	9918	9908	9914	991	9912	....	991	9882
10	6402.245	2441	2452	2471	....	2456	....	246	2392
9	6506.528	5270	5285	5279	534	5272	5281	527	....
4	6532.883	8829	883	8823	885	8844	8810	881	....
5	6598.953	9528	953	9527	953	9540	9525	953	....
8	6678.276	2758	2755	2766	276	2752	2767	275	....
5	6717.043	0428	0423	0430	044	0464	0444	042	....
8	6929.468	4675	4683	4677	470	4675	4678	465	....
3	7024.049	....	....	....	....	....	0486	....	....
9	7032.413	4132	4136	4123	415	4111	4118	410	....
3	7059.111	....	....	....	....	....	111	....	....

TABLE 1.—Interferometer Measurements of Wave Lengths in the Neon Spectrum—Continued

I	λ Adopted	1	2	3	4	5	6	Meissner	Priest
5	7173.939	....	....	....	....	937	9400	938	....
8	7245.167	169	....	....	....	162	1688	165	....
6	7438.902	....	....	....	....	903	9016	885	....
5	7488.885	....	....	....	....	....	885	....	....
5	7535.784	....	....	....	....	....	784	....	....
3	7544.050	....	....	....	....	....	050	....	....
4	8136.408	....	....	....	....	....	408	....	....
4	8300.369	....	....	....	....	....	369	....	....
8	8377.606	....	....	....	....	....	606	....	....
4	8495.380	....	....	....	....	....	380	....	....

The column λ in Table 1 gives, for the most part, the mean of our interferometer comparisons of neon wave lengths with the cadmium standard. The values of 12 long waves are given relative to shorter neon waves. These final results are given to three decimal places and are preceded by a column indicating the relative intensities of the spectral lines.

The relative accuracy of the values in this column may be judged by considering columns 1 and 6. If the values in these columns are given to four decimal places, the line has been well observed and the wave length is probably correct to one or two thousandths of an angstrom. When the value is given to only three places in column 1 or 6, the line is not so well observed, either on account of its being too faint or too close to another line for accurate measurement. The constant differences, discussed below, indicate that the accuracy obtained in measuring of the very faint lines is still considerable. The line 3369 is a very close double; this line and the pair at 3593 A may be in error by as much as 0.01 A. All the other lines are probably correct to within four thousandths of one angstrom.

Meissner's values are in remarkably close accord with ours except for one or two lines. The same can be said of Priest's values. The largest discrepancy occurs in the wave length 6402 A, which is the strongest line in the neon spectrum. Priest's value, 6402.2392 A, was nearly reproduced by Takamine[17] who, by direct comparison with the cadmium standard 6438.4696 A, found 6402.2395 A for the neon wave length. Our value is about one part in a million larger and a similar result is also given by Meissner. The reason for this disagreement is not apparent.

[17] Takamine, Proc. Tokyo Math.-Phys. Soc., 8, p. 9; 1915.

2. GRATING MEASUREMENTS

In addition to the stronger lines in the neon spectrum which were measured by interferometer methods, many faint lines in the red and infra-red spectral regions were measured from photographs obtained with a concave diffraction grating. A description of the grating appears elsewhere in this Bulletin.[18]

Plates stained with pinacyanol or dicyanin were used in this spectrum photography. Some of the wave lengths were measured in terms of the interferometer values of neon lines and the remainder were obtained from secondary standards in the spectrum of the iron arc. More work of this kind is desirable but it is not feasible for us at present. The results thus far secured are therefore presented in Table 2 in this paper. The wave lengths are given to hundredths of an angstrom and are probably correct in most cases to 2 or 3 units in the last place. Most of the lines in Table 2 are so faint compared with those in Table 1 that their intensities have been indicated by zero.

TABLE 2.—Grating Measurements of Wave Lengths in the Neon Spectrum

λ	I	λ	I	λ	I	λ	I
5343.22	4	5974.65	1	6272.97	1	7472.38	2
5689.60	1	5982.50	0	6275.98	0	7937.02	1
5719.21	1	5987.90	2	6293.68	1	7943.18	3
5748.30	2	*a* 5991.63	1	6313.61	1	8082.45	3
5760.58	1	6000.90	0	6328.14	2	8118.51	1
5804.44	2	*a* 6046.08	0	6330.87	1	8128.84	0
5811.42	1	6064.50	0	6351.75	0	8259.32	1
5816.57	0	6117.96	1	6364.92	0	8265.96	2
5828.92	0	6128.44	3	6409.67	1	8267.20	0
a 5868.35	0	6150.24	1	6421.66	1	8365.72	0
5872.19	0	6156.06	0	6444.68	1	8376.39	0
5872.85	2	6174.93	1	*a* 6602.75	0	8418.38	2
5902.48	2	6182.13	1	6639.94	0	8591.24	2
5906.44	1	6189.02	0	6652.06	2	8634.60	2
5913.62	1	6193.04	0	6666.81	0	8654.38	2
5918.93	1	6205.73	1	6737.96	0	8679.55	1
5934.45	0	6213.84	2	6759.54	0	8681.80	1
5939.38	0	6225.72	0	7112.29	0	8780.64	2
a 5961.63	1	6246.70	1	7242.68	0	8783.71	1
a 5965.48	2	6258.77	1	7304.90	0		

[18] This Bulletin, 14, p. 371: 1917.

a There is a ghost near to each of these lines and the value given for its wave length may be in error on this account. The line at 6401.0 is very faint on our plates. The fact that Watson finds this line to be strong suggests that it may be due to an impurity.

3. CONSTANT FREQUENCY DIFFERENCES

It is well known that all of the lines in the ordinary helium spectrum can be placed in six series. The spectra of the other rare gases, however, seem to be differently constructed. Rossi [19] has found series relationships among some faint neon lines, but he was unable to find them among the stronger lines. In a search for series among the stronger lines of neon Watson [20] found that most of these lines belonged to either triplets or quadruplets in which the frequency differences between corresponding members were constant. These constant frequency differences are very interesting in the light of accurate measurements. Meissner [21] has already described some of these frequency differences resulting from his wave-length measurements of the strong lines in the red part of the neon spectrum. Our wave-length measurements are somewhat more extensive and include determinations of wave-lengths for most of the strong lines in one of the ultra-violet groups. All cases which seem to present constant frequency differences are collected in Table 3. This table is arranged on the principle that each group is a quadruplet. Fifteen groups are shown, six of which are complete quadruplets. Six of the groups lack the second member, one lacks the third, and two lack the second and fourth members. Watson found eight or possibly nine additional groups among shorter wave lengths (2911 A to 3168 A). The values given to three places of decimals in Table 3 are derived from interferometer measurements of wave lengths given in Table 1, while those given to two decimal places are obtained from grating measurements. Thirty-seven of the 55 strong neon lines represented in Table 1 seem to be connected by frequency differences which justify their appearance in Table 3. This accounts for all the strong lines in the yellow and red except 5852 A and 6402 A. The line 6074 A was heretofore also considered an exception and its relation to 6652 A may be fortuitous. Of the 24 strong lines in the ultra-violet spectrum between 3369 A and 3754 A all find a place in Table 3 except 3472 A and 3520 A.

[19] Rossi, Phil. Mag., 26, p. 981; 1913.
[20] Watson, Astroph. Jl., 33, p. 399; 1911.
[21] Meissner, Phys. Zeitschr., 17, p. 549; 1916.

TABLE 3.—Frequency Differences in the Neon Spectrum

No.	Intensity	λ I. A. in air	λ I. A. in vacuum	Frequency in vacuum ν_1 ν_2 ν_3 ν_4	$\nu_2-\nu_1$ $\nu_3-\nu_2$ $\nu_4-\nu_3$	$\nu_2-\nu_1$ $\nu_3-\nu_1$ $\nu_4-\nu_1$
1	3	8082.45	8084.67	12 369.09	1070.06	1070.06
2	6	7438.902	7440.948	13 439.149	359.358	1429.42
3	8	7245.167	7247.161	13 798.507	417.450	1846.87
4	9	7032.413	7034.349	14 215.957		
1	5	7173.939	7175.913	13 935.509		
2						1429.434
3	9	6506.528	6508.322	15 364.943	417.447	1846.881
4	8	6334.428	6336.176	15 782.390		
1	3	7024.049	7025.983	14 232.885	1070.073	1070.073
2	4	6532.883	6534.684	15 302.958	359.358	1429.431
3	8	6382.991	6584.752	15 662.316	417.449	1846.880
4	4	6217.280	6218.996	16 079.765		
1	8	6929.468	6931.376	14 427.150		
2						1429.433
3	4	6304.789	6306.529	15 856.583	417.450	1846.883
4	9	6143.062	6144.758	16 274.033		
1	5	6717.043	6718.894	14 883.402	1070.079	1070.079
2	7	6266.495	6268.225	15 953.481	359.39	1429.47
3	3	6128.44	6130.13	16 312.87	417.41	1846.880
4	4	5975.534	5977.185	16 730.282		
1	8	6678.276	6680.116	14 969.799		
2						1429.452
3	8	6096.163	6097.847	16 399.231	417.448	1846.880
4	8	5944.834	5946.477	18 816.679		
1	3	6652.06	6653.89	15 028.80		
2						1429.35
3	7	6074.338	6076.016	16 458.153		
4						
1	5	6598.953	6600.772	15 149.743	1070.079	1070.079
2	5	6163.594	6165.296	16 219.822	359.354	1429.433
3	4	6029.997	6031.663	16 579.176	417.448	1846.881
4	6	5881.895	5883.521	16 996.624		
1	2	3754.17	3755.23	26 629.51	1069.74	
2	2	3609.18	3610.21	27 699.25		
3						1846.48
4	3	3510.73	3511.73	28 475.99		
1	4	3701.16	3702.21	27 010.90		
2						1428.95
3	5	3515.192	3516.194	28 439.846	417.446	1846.39
4	4	3464.340	3465.329	28 857.292		
1	3	3685.71	3686.76	27 124.12		
2						1429.23
3	4	3501.218	3502.216	28 553.350	417.67	1846.90
4	3	3450.74	3451.72	28 971.02		
1	3	3682.22	3683.26	27 149.83		
2						1429.24
3	4	3498.067	3499.064	28 579.070	417.450	1846.69
4	6	3447.705	3448.689	28 996.523		
1	5	3633.664	3634.696	27 512.618		
2						1429.409
3	6	3454.197	3455.183	28 942.027		
4						
1	5	3600.170	3601.193	27 768.573	1070.065	1070.065
2	5	3466.581	3467.570	28 838.638	359.14	1429.21
3	2	3423.94	3424.92	29 197.78	418.11	1847.32
4	3	3375.60	3376.57	29 615.89		
1	4	3593.634	3594.656	27 819.077	1070.019	1070.019
2	5	3460.526	3461.514	28 889.096	360.225	1430.244
3	6	3417.906	2418.883	29 249.321	416.607	1846.851
4	5	3369.906	3370.870	29 665.928		

The agreement between different sets of the constant frequency differences is remarkable, especially for the red lines, whose wave lengths have been more thoroughly investigated than those of

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the ultra-violet group. 3593 A is a close double line and could not be accurately measured. This no doubt accounts for the low value of the difference (1070.019). 3369 A is also double, but the components could not be separated. Although the other two lines of this quadruplet never appeared to be double, it is possible that they also are very close pairs.

In terms of the frequency or numbers of waves per centimeter these differences are constant to one part in four or five millions and this limit to the constancy is imposed by the uncertainty in the wave-length measurements. If the frequency differences are assumed to be in reality strictly constant, our values afford a test for the accuracy of our wave-length determinations and show that the interferometer measurements are rarely in error by more than one one-thousandth of an angstrom.

By averaging the frequency differences derived from the interferometer measurements of the long waves we arrive at the following frequency relations

$$\nu_2 = \nu_1 + 1070.077$$
$$\nu_3 = \nu_1 + 1429.434 = \nu_2 + 359.356$$
$$\nu_4 = \nu_1 + 1846.881 = \nu_2 + 776.805 = \nu_3 + 417.449$$

The significance of these wonderful constant differences among frequencies is very little understood at the present time.

Considering only the strong lines the spectrum of neon falls naturally into three groups of lines which diminish in average intensity from the red to the ultra-violet end. Each of these three large groups contains smaller groups in which the frequencies of homologous members differ by a constant as shown above, but there appears to be no definite relation between the intensities of members of the same or of different groups. In some cases the members of a quadruplet have, roughly, the same intensities, while in others strong lines are associated with very faint ones. It may be that all of the groups are really quadruple and that the missing lines have not yet been observed on account of their small intensities.

Certain regularities have also been observed among the intense red neon lines from the point of view of magnetic separations. The Zeeman effect on the spectrum lines of neon was first studied by Lohmann [22] and more extensively by Takamine and Yamada.[23]

[22] Lohmann, Diss., Halle; 1907.

[23] Takamine and Yamada, Proc. Tokyo Math.-Phys. Soc., 7, p. 278; 1914.

The magnetic separations of the corresponding members of Watson's quadruplets and triplets were found to be quite similar except in a few cases. Omitting the first members of these groups, the remaining members show magnetic components which increase in number by three from one to the next. In quadruplets, all lines designated by λ_2 become triplets when observed transverse to a magnetic field, λ_3 become sextets, and λ_4 nonets. In the case of triplet groups, λ_2 show as nonets and λ_3 give 12 components.

Furthermore, not only the magnetic separations, but also the intensity distribution in nonets is the same throughout each type of line. The physical significance and interpretation of all these regularities in the spectrum of neon is one of the attractive problems in physical science at the present time.

IV. SUMMARY

The wave lengths of 55 lines in the neon spectrum have been measured by means of the interferometer. These lines lie in the region 3369 A to 8495 A. The strong lines in the visible region of the spectrum have been observed with great accuracy, the probable error being one part in several millions, or less than one-tenth the width of the line. These strong lines were observed by means of three different pairs of interferometer plates which were each used on several interferometers. The ultra-violet lines and all the strong lines in the visible were compared directly with the fundamental standard 6438 A. Some of the deep-red and infra-red lines were compared with well-determined lines in the visible neon spectrum.

Seventy-nine faint lines in the visible and infra-red neon spectrum have been measured by means of a concave grating. The probable error of these grating measurements is one or two hundredths angstrom. The region covered by the grating observations extends from 5343 A to 8783 A.

The constant differences discovered by Watson are found to hold with remarkable exactness in the case of lines which are strong enough to be measured with the highest accuracy. In fact, the differences are exactly constant within the limits set by the accuracy of the wave lengths.

WASHINGTON, April 6, 1918.