Doppler Effect in Spectra of Positive Rays of Uniform Velocity in Argon, Neon, Helium

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Ions of argon, neon, helium, formed in a low voltage arc have been accelerated to high speeds in a short electric field, forming beams of positive ions which all have the same energy. The spectra of the beams of positive rays of uniform energy observed in the direction of motion show a characteristic Doppler effect, with displaced lines fully as sharp as the rest lines. With the exception of the very intense λ3418 of neon, the arc lines of argon and neon have no Doppler effect, while the lines of the first spark spectrum are accompanied by sharp displaced lines only slightly less intense than the rest lines, whose separation corresponds accurately to the speeds acquired by singly charged ions in the accelerating field, for velocities 9000 to 28,000 volts and several lines of higher spark spectra were observed with displaced lines also corresponding to singly charged ions. Satisfactory observations are made at pressure about 5×10^{-3} mm, the intensity and sharpness of the displaced lines diminishing with increasing pressure. In helium, the arc lines show relatively faint displaced lines corresponding to singly charged ions; one spark line λ4686 was accompanied by a relatively intense displaced line, while the only other spark line observed, λ4541, had no Doppler effect.

CANAL rays in passing through a gas excite a spectrum characteristic of the gas at rest and also radiate themselves. Viewed in the direction of motion, the spectrum from the moving particles exhibits a Doppler displacement towards the shorter wave-lengths. As usually produced, the canal ray particles do not all have the same speed, because of change of charge within the accelerating field; hence the spectral lines showing the Doppler shift are correspondingly diffuse, their maximum displacements less than anticipated from the magnitude of the accelerating field. In general, the displaced lines of the spark spectra are more intense than the displaced lines of the arc spectra for high voltages.[1]

In the present experiments, the Doppler effect has been investigated in argon, neon and helium for beams of positive rays in which all the particles have nearly the same energy. In marked contrast to previous observations, the displaced lines are sharp and their positions are calculable from the magnitude of the accelerating field within the accuracy of observation. The beam of uniform energy was obtained by the method developed by Dempster, in which ions formed in a low-voltage arc traverse an accelerating field too short for an appreciable number of particles to change charge.[2, 3, 4]

APPARATUS AND METHOD

The discharge tube shown in Fig. 1 is Pyrex glass, 45 cm long by 4 cm diam. One end is ground smooth and fitted with a quartz window

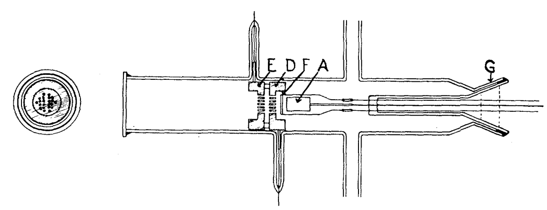

FIG. 1. Discharge tube for production of beams of positive ions of uniform energy.

waxed in position. F is an oxide-coated filament; D, E, are steel electrodes held in place by glass rods. The perforations in D, E, are similarly cut as shown in the end-on view, in such a way that the solid strip in the center of the electrodes conceals the filament F. Before mounting the

[1] Handbuch d. Physik **24**, 112–136, and Wien-Harms Handbuch d. Experimentalphysik **14**, 643 and following.

[2] H. F. Batho and A. J. Dempster, Astrophys. J. **75**, 34 (1932).

[3] Philip Rudnick, Phys. Rev. **38**, 1342 (1931).

[4] H. F. Batho, Phys. Rev. **42**, 753 (1932).

electrodes were partially outgassed by heating in vacuo to redness. The waxed joint G allowed easy removal of the anode and the filament for renewal or adjustment.

The filament F and the perforated electrode D were kept at ground potential throughout, the anode A was kept about 100 volts positive, while the electrode E was highly negative, from 9000 to 28,000 volts. Thus positive ions were formed in the arc AF, drifted into the narrow accelerating space $DE-3.75$ mm—then passed into the observation space beyond.

The vacuum was produced by a Gaede mercury diffusion pump, backed by a Cenco Hyvac oil pump. Pressures were measured with a McLeod gauge. A trap immersed in liquid air served to keep mercury vapor from the discharge tube.

High negative potential from a 2.4 kilowatt transformer, rectified and smoothed by a kenotron and condenser, reached electrode E through a high resistance. For convenience in estimating the voltage across DE, before the experiment was begun a micrometer spark gap with inch spheres was connected across DE, a voltmeter across the primary of the transformer. The primary voltage was calibrated over the range used, in terms of the spark gap for breakdown and the equivalent high potential.[5] The applied high potential was kept constant by maintaining steady voltmeter readings across the primary of the transformer.

The gases were purified by evaporating a small bit of magnesium metal in a side-tube of the storage vessel with an induction heater; the system was usually refilled for each photograph.

Two spectrographs were used, for the visible a Steinheil instrument with three large glass prisms, dispersion 58.3A per mm at $H\beta$, 32.4 at $H\gamma$; and for the ultraviolet, a Hilger quartz single prism spectrograph, type E-3, dispersion 37A per mm at λ4000, 14.6 at λ3000. The positive ray beam, which was about 12 cm long, was viewed end-on, the image of the unperforated central strip of electrode E being formed on the slit of the spectrograph so that no light from the filament of the arc behind it could enter the spectrograph directly. Eastman 40 plates were used.

[5] W. Peek, *Dielectric Phenomena in High-Voltage Engineering*, McGraw-Hill (1929).

Experimental Results

Photographs were taken, with the two spectrographs, of the canal ray spectra of neon, argon, and helium, covering the range of wave-lengths from about 2500 to 5000A. The applied potentials varied from 9000 to 28,000 volts. Gas pressures between 10^{-2} and 10^{-3} mm Hg, requiring exposure times from one hour to about 20 hours, gave satisfactory pictures. The effect of increasing the pressure as far as 3×10^{-1} mm was studied in neon.

The appearance of the photographs taken at the lower pressures is characteristic, each spectrum appearing to consist mainly of doublets. The displaced line in all cases is as sharp as the undisplaced line, indicating the uniformity of speed among the moving particles, and is usually slightly less intense. The intensity of both the rest lines and the displaced lines increases appreciably with increasing speeds of the moving particles. The only impurity lines were $H\beta$ and $H\gamma$ and Hg 4358.

Neon

Doppler effects in neon canal rays were observed by Dorn[6] in 1909 for a few lines in the red part of the arc spectrum and in 1931 by Romig[7] who, with unhomogeneous rays of 24,000 volts maximum velocity found the effect for many lines of the spark spectrum and strongly for two lines of the arc spectrum.

In the present experiments, the neon photographs showed sharp, intense Doppler lines, but

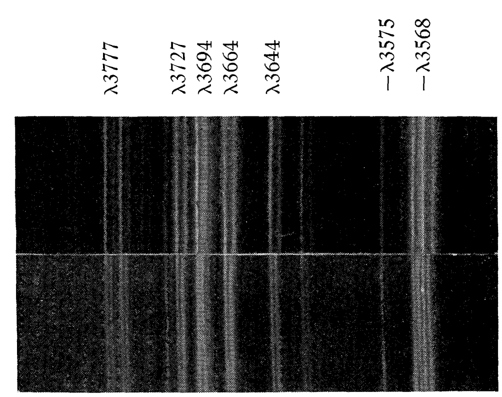

FIG. 2. Doppler effect spectra of neon canal rays, 26,350 and 9100 volts.

[6] E. Dorn, Phys. Zeits. **10**, 614 (1909).
[7] W. Romig, Phys. Rev. **38**, 1709 (1931).

TABLE I. *Neon lines which show Doppler effect.*

International A	Intensity	International A	Intensity
4569.02	5	3355.09	7
4522.65	4	3345.49	3
4428.56	6	3344.44	5
4409.31	7	3334.89	10
4397.94x	6	3327.22	5
4391.94	7	3323.79	7
4379.47	6	3319.76	3
4322.66	1	3297.74	8
4322.26	2	3244.15	5
4290.40	6	3232.38	3
4231.61	5	3230.13	5
4219.74	6	3224.84	5
3942.19	3	3218.22	8
3777.14	8	3214.33?	5
3766.28	8	3198.58	6
3751.25	4	3097.15	2
3734.94	7	3093.99	4
3727.09	9	3059.15x	3
3713.07	10	3054.70	5
3709.66	7	3047.60	6
3694.19	10	3034.49	5
3664.05	9	3028.90	4
3643.90	5	3027.07	4
3594.15	2	3001.72	7
3574.65	5	2967.20	3
3568.47	6	2955.77	7
3542.89	7	2866.60 II Spark	6
3481.97	6	2822.97 II Spark	4
3477.66	3	2792.04	4
3417.90 Arc	10	2777.60 II Spark	5
3418.00	6	2678.65 II Spark	3
3406.88	5	2677.90 II Spark	5
3404.77	4	2613.41 II Spark	4
3392.81	7	2610.04 II Spark	5
3388.47	5	2595.66 II Spark	6
3378.28	5	2593.57 II Spark	6
3367.25	6	2590.01 II Spark	7
3360.63	5		

the appearance of the spectrum was quite unlike the normal neon Geissler tube spectrum. That this was neon was verified from the displacements of the lines, which agreed with that of singly charged ions of atomic weight 20. The spectrum was found to be the first spark spectrum, with a few higher order spark lines and some of the more intense arc lines. The two typical pictures of Fig. 2, in which the rest lines are matched and appear continuous, show clearly the sharpness and intensity of the Doppler lines, and the different displacements at two different speeds.

Table I lists the lines which show the Doppler effect. Unless otherwise specified, all lines belong to the first spark spectrum. Lines marked x show Doppler effect, but the position of neighboring lines prevented measurement of the displacement. The wave-length and classification of Bloch[8] were followed for the spark lines, those of Paschen[9] for the arc. While most of these lines belong to the first spark spectrum, several lines of the second spark spectrum also exhibit Doppler effect, as do the very intense unresolved arc lines 3417.9 and 3418.0. The appearance of their displaced lines was not distinguishable from that of the displaced first spark lines in respect to sharpness, intensity or distance of separation. In no case was more than one displaced line observed associated with a line. It would not have been possible in these experiments to resolve the displaced line corresponding to the less abundant neon isotope of mass 22.

Measurement of the separations on two spectrograms with applied voltages 26,350 and 9100 showed that all the displacements corresponded to the velocity acquired by a singly charged ion traversing the entire accelerating field. From the first plate, calculating from the voltage 26,350, the value of $d\lambda/\lambda$ is 0.00168 while the average measured value is 0.00164; from the other, voltage 9100, the values are 0.00099 and 0.00101.

Effect of pressure. A series of photographs was made, the pressure of the neon being increased to 3×10^{-1} mm, when sparking took place between the electrodes, then 1.5 mm apart. With increase of pressure the observed Doppler lines became less sharp and decreased in intensity relative to the rest lines. At pressure 3×10^{-1} only the most intense lines were accompanied by displaced lines, which were faint and diffuse and extended a considerable distance towards the rest lines.

The appearance of the displaced lines and their extension towards the rest lines suggest that most of the moving ions have lost charge in the accelerating field, attaining all velocities up to the maximum. The weakening of the displaced lines may also be due to the fact that the normal rate of decay of radiation from the group of excited particles is hastened by collision and neutralization of the radiating particles, since the time of decay of radiation intensity to $1/e$ of its initial value is about 10^{-8} seconds,[10] the same

[8] L. Bloch, J. de Physique et le Radium **7**, 129 (1926).

[9] F. Paschen, Ann. d. Physik **60**, 405 (1919).

[10] W. Wien, Ann. d. Physik **73**, 483 (1924); H. Kerschbaum, Ann. d. Physik **79**, 465 (1926).

order of duration as the life before neutralization of a moving ion at the speed and pressure here considered.[3, 4]

Argon

Dorn,[11] Stark and Kirschbaum[12] and Friedersdorff[13] have studied Doppler effects in argon canal rays under various conditions, the latter workers reporting broad diffuse displaced lines accompanying both the "red" and the "blue" spectra, with regions of maximum intensity apparently corresponding to velocities of multiply charged ions. In the present experiments, photographs were taken with both spectrographs. All the blue, first spark lines of considerable intensity were accompanied by sharp displaced lines of slightly less intensity, while no red arc lines showed any Doppler effect whatever.

Table II lists the argon lines for which Doppler effect was observed; separations were not measured for lines marked *x*, owing to the proximity of other lines. Wave-length tables of Rosenthal[14] and Bloch, Bloch and Dejardin[15] were used for the blue spectrum, that of Meissner[16] for the red spectrum.

In distinction to the earlier observations, the shifted lines were sharp, and their displacements corresponded accurately to those calculated from the velocity acquired by a singly charged argon ion falling through the entire applied potential difference. For example, at 20,400 volts the average measured value of $d\lambda/\lambda$ is 0.00101, the calculated value is 0.00106; at 26,000 volts the measured value is 0.00119, that calculated is 0.0012; and at 28,000 volts these values are 0.00124 and 0.00123.

TABLE II. *Argon lines showing the Doppler effect.*

Internat'l. A	Intensity	Internat'l. A	Intensity	Internat'l. A	Intensity
49 65.12	7	43 09.25	3	35 82.35?*x*	8
49 33.24	6	43 09.11	2	35 76.62	10
48 79.9	12	43 00.66	6	35 61.04	6
48 67.59*x*	3	42 77.55*x*	8	35 59.53	6
48 47.90	8	42 66 53	10	35 45.84 }	9
48 06.07	20	42 37.23*x*	7	35 45.58 }	10
47 64.89	10	42 28.18	7	35 14.39	9
47 35.93	15	41 89.67?	4	34 91.54 }	8
47 26.91	10	41 31.73	8	34 91.24 }	6
46 57.94	9	41 03.91	10	34 76.74	6
46 37.25	6	40 76.96 } *x*	4	33 88.54	7
46 09.60	15	40 76.64 } *x*	5	32 81.72	6
45 89.93	9	40 72.40 }	7	{ 31 28.00	4 }
45 79.39	8	40 72.01 }	9	{ Rowland's Sys.,	II Spark }
45 47.78*x*	5	40 52.94*x*	5	30 99.97	4
45 45.08	10	40 42.91*x*	8	30 93.41	8
44 81.8	8	40 38.82	7	30 85.05	4
44 33.83	5	40 13.87?	10	30 82.99	4
44 31.02*x*	8	39 46.10*x*	7	29 42.90	8
44 30.18*x*	9	38 68.53	8	{ 28 84.21?	2 }
44 26.01	15	38 50.57	15	{	II Spark }
44 01.02 }	7	{ 38 19.04?	4 }		
44 00.09 }	6	{ Rowland's Sys.,	II Spark }		
43 83.79	4	38 09.49	7		
43 79.74*x*	8	37 99.39	6		
43 75.96	5	37 80.84	8		
43 71.36	8	37 65.27*x*	6		
43 70.76	6	37 37.89*x*	6		
43 62.07?	5	37 29.29	10		
43 52.23	6	37 17.17	5		
43 48.11	20	36 22.15	6		
43 31.25	10	35 88.44*x*	10		

[11] E. Dorn, Phys. Zeits. **8**, 589 (1907).

[12] J. Stark, H. Kirschbaum, Ann. d. Physik **42**, 255 (1913).

[13] K. Friedersdorff, Ann. d. Physik **47**, 737 (1915).

[14] A. H. Rosenthal, Ann. d. Physik **4**, 49 (1930).

[15] L. Bloch, E. Bloch and G. Déjardin, Ann. de Physique **2**, 480 (1924).

[16] K. W. Meissner, Zeits. f. Physik **39**, 172 (1926).

The three second spark lines which appeared, 3819.30, 3128.00, 2884.21, all have displaced lines whose separations correspond to singly charged ions. No line was observed whose displacement corresponded to a multiply charged ion.

Helium

Doppler effects have long been known for some lines in the visible spectrum of helium canal rays.[17] Stark[18] reported two maxima of intensity in the displaced strip when the helium ions were sent into mixtures of helium with hydrogen or iodine vapor.

In the present experiments, the results obtained with helium differed markedly from those with neon and argon. The plates showed displaced lines accompanying the lines of the arc spectrum, apparently all of the same intensity relative to the rest lines, very much less intense but quite as sharp.

TABLE III. *Helium lines for which Doppler effect is observed.*

International A	International A	International A
5047.7*x*	4437.552*x*	4009.270*x*
5015.68	4387.931	3964.732
4921.9	4168.965*x*	3888.649
4713.373 }	4143.759	3867.631 } *x*
4713.143 }	4120.989 }	3867.477 } *x*
4685.75 Spark	4120.817 }	3819.761 } *x*
4471.681 }	4026.363 }	3819.614 } *x*
4471.479 }	4026.189 }	3187.744*x*

Table III lists the helium lines for which the Doppler effect was observed, lines not previously reported are marked *x*.

Since at least one line is here represented belonging to each singlet series and each doublet series of the helium spectrum, presumably all the arc lines show the Doppler effect. Insufficient intensity probably caused the earlier failures to observe many of the displacements.

The spark line 4686 appearing on several of the plates differed from the arc lines in that the displaced line was of intensity comparable to the rest line, in accordance with Rau's[19] observation of its characteristic appearance. The same plates also showed the Pickering spark line 4541, stronger than 4686, but this line had no accompanying displaced line.

Discussion

The observed sharpness of the displaced lines was anticipated, as the measurements of Rudnick and Batho on the distance travelled by a positive ion before neutralization show that few ions change their charge in the length of the accelerating field at these pressures and speeds and thus the beam contains particles of sensibly uniform energy. The absence of displacements corresponding to velocities of multiply charged ions accords with the observations of Bleakney[20] that most of the ions formed by single electron impact in a 100-volt arc in neon, argon, helium, are singly charged.

The beam of moving particles for most of its observed length has its equilibrium distribution mostly neutrals, some positive ions;[21] but the almost entire lack of Doppler effect in the arc spectrum indicates that the excitation of the moving neutrals by collision with particles at rest does not result in arc radiation in considerable intensity, nor does the neutralization of the moving positives. Collisions between moving neutrals and neutrals at rest must result on the average in the same degree of excitation of the moving particles and the rest particles. If the greater number of such collisions produces an excited ion and a normal atom, or two excited ions, as is possible on closely interpenetrating collisions,[21] this could account for the observed Doppler effect in the spark spectrum, with the displaced and rest lines of comparable intensity.

The behavior of the three gases is probably similar and it is possible that the neon and argon as well as the helium have Doppler effect in their

[17] H. Rau, Phys. Zeits. **8**, 360 (1907); G. F. Hull, Astrophys, J. **25**, 1 (1907); H. Gerdien, R. Holm, Ann. d. Physik **27**, 844 (1908).

[18] J. Stark, Jahrbuch der Radium und Elektronik **14**, 139 (1917).

[19] H. Rau, Ann. d. Physik **73**, 271 (1924).

[20] W. Bleakney, Phys. Rev. **36**, 1303 (1930).

[21] W. Weizel and O. Beeck, Zeits. f. Physik **76**, 3–4, 250 (1932).

arc spectra but with displaced lines too faint to be perceived in the present experiments, except for the strong neon arc lines at 3418.

From the measured displacement of the displaced spark lines of order higher than the first, observed in the spectra of neon and argon, these lines were radiated from particles which passed through the accelerating field with only a single charge, afterwards becoming more highly charged and excited in the observation space.

The writer acknowledges with pleasure the gracious assistance and encouragement of Professor A. J. Dempster, at whose suggestion these experiments were performed.

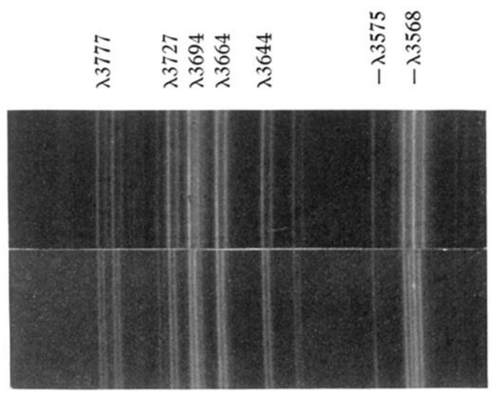

FIG. 2. Doppler effect spectra of neon canal rays, 26,350 and 9100 volts.