ART. II.—*The Spectra of Argon*; by JOHN TROWBRIDGE
and THEODORE WILLIAM RICHARDS.

It is well known that argon possesses at least two marked spectra—one, termed the red, which is chiefly characterized by red lines; and another called the blue, which, as its name signifies, is strongly marked by blue lines.

In studying these spectra by means of a high tension accumulator, we have been led to observe carefully the electrical conditions necessary for producing them. It is obvious that a battery of a large number of cells is the most suitable source for the study of discharges of electricity through gases. Especially is this true of a storage battery; for the readiness with which it can be charged by a dynamo, the constancy of the electromotive force (about 2.1 volts per cell), the ease with which it can be coupled for quantity or tension; and the steadiness of the discharge afforded by it, make such a battery far superior to an induction coil or to an electrical machine.

With an induction coil the discharge is not unidirectional and is affected by the necessary irregularities of the break. These irregularities make themselves felt in a marked degree when a condenser is used in the secondary circuit. The electrical machine gives an intermittent current, and has a varying capacity. The advantages of a battery for the study of the discharge of electricity through gases have been pointed out by De la Rue and Miller and by Hittorf.* These investigators worked with voltaic cells which were not constant and which required great oversight and continual renewals. In our investigations we are using a lead accumulator of the Planté type; and we find it highly advantageous for spectroscopic work; for by means of the steady current afforded by it, one can study the spectra of gases under especially good conditions.

Our battery consists of five thousand cells, so arranged that they may be disconnected and wholly reconnected in any desired manner in less than a minute. The electromotive force of the complete series is somewhat over ten thousand volts, but when the cells are connected for quantity, they may be readily charged by means of a dynamo giving a tension of only sixty volts. The insulation of the terminals of this battery was a matter of some difficulty, for even dry wood allows considerable leakage from one case of cells to another; but by the plentiful use of paraffin, mica, and vulcanite, the problem was solved with reasonable success. The discharge from only a very small fraction of the battery produced a most uncom-

* Ann. der Phys. und Chem. (N. F.), vol. vii, 1879, p. 553.

portable shock, and it is probable that the discharge of the whole battery would be instantly fatal. The great heat of this full discharge immediately shatters a Geissler tube, the glass being splintered throughout the whole length of the capillary. Hence a resistance of several million ohms was usually interposed between the battery and the rest of the apparatus. This resistance was also of service in protecting the experimenters from serious accidental shocks. Ordinary distilled water contained in long tubes with movable electrodes was the most convenient resistance for our purpose; dilute solutions of cadmic iodide in amyl alcohol and of cadmic sulphate in water between cadmium electrodes, were also sometimes used. Unless these liquids are contained in tubes of rather large diameter, they are likely to cause irregularities by boiling under the influence of the heat of the current. Graphite resistances are too combustible for the purpose.

The argon used in our experiments was very kindly given to one of us by Lord Rayleigh. It was a portion of the purest preparation which had been used in his final determinations of the density of the gas; and our tubes were carefully filled with it by the kindness of F. O. R. Götze, of Leipzig. The preliminary work described in this paper was chiefly done with a single tube containing gas at a pressure of about 1^{mm} . The tube had a wide capillary and was about 15^{cm} in total length. In such a tube, the red glow of argon is readily obtained with a voltage of about two thousand, but not with much less. A higher tension of gas demands a higher tension of electricity in order to start the discharge, no matter how much or how little other resistance is interposed; but when the glow has once started it is continued by means of a much smaller electromotive force. This is shown by the fact that a Thomson electrostatic voltmeter, connected with the terminals of the Geissler tube, indicated differences of potential between the ends of the tube ranging from six hundred and thirty volts upward. De la Rue and Miller, who found no potential difference between the ends of Geissler tubes, must have been working with discontinuous discharges. Crookes's estimate that 27,600 volts are necessary to produce the red spectrum is evidently excessive.

The introduction of a capacity between the terminals of the Geissler tube, for example, two plates of metal sixteen hundred square centimeters in area separated by plate glass one centimeter thick, made no difference in the red glow, so long as the connections were good and the condenser quiet.* As soon as a spark gap was introduced, or the condenser began to

* Sir W. Thomson (Lord Kelvin): *Papers on Electrostatics and Magnetism*. MacMillan, 1872, p. 236.

emit the humming sound peculiar to it, the beautiful blue glow so characteristic of argon immediately appeared.

If this light is examined by a revolving mirror it is seen to consist of intermittent discharges. The battery charges the condenser to the potential necessary to produce a spark between the terminal of the spark gap. The discharge of this accumulated electricity is produced in the tube and then the operation is repeated. The time interval between the discharges is evidently a function of the capacity of the condenser, as well as of the electromotive force of the battery and the resistance between it and the condenser.

The accurate determinations of the potential and current strength of the intermittent blue discharge is a matter of some difficulty; and at present we feel hardly in position to make a definite statement regarding these measurements. However, the potential required certainly cannot be greater than two thousand volts,—the electromotive force of the battery which will easily produce the blue glow. Here again, Crookes's estimate of far above 27,000 volts was very much too large.

Since it is necessary to employ a condenser to produce the blue spectrum of argon, we were led to examine the electrical conditions which are necessary for the discharge. In the circuit with the tube containing argon, between the tube and one of the plates of the condenser, we first interposed a small coil of about eight ohms resistance, having a self-induction of $\cdot 015$ of a henry. The blue glow changed to the red glow. We then modified the self-induction and discovered that even the self-induction of the leads to the tube, which consisted of a few feet of uncoiled wire, undoubtedly modified the blue discharge, for an amount of induction equivalent to $\cdot 000051$ henry had a marked effect in diminishing the brilliancy of the blue glow.

A comparatively small ohmic resistance substituted for the impedance of the self-induction between the tube and one plate of the condenser produced precisely the same effect as this coil, causing a complete transformation from blue to red. The change from blue to red is so marked that a tube of argon may well serve as an inductometer of some sensitiveness, as well as a means of comparing the influence of self-induction with ohmic resistance. The effect of impedance or resistance must be to prolong or to damp the oscillations of the condenser discharge. Indeed, the resistance of the tube itself may be so great as to damp the oscillations without the need of the introduction of outside resistance or self-induction; therefore argon at high tension gives the red glow with a condenser and rate of oscillations which are quite capable of producing the blue glow in a tube of lower tension.

Kayser* criticises Crookes's statement that a condenser and a spark gap are necessary for the production of the blue spectrum. He finds that with a lower pressure in the tube than 2^{mm} the blue spectrum can be readily obtained without condensers and spark gaps. He also states that it is much easier to produce the pure blue spectrum than the pure red. In order to obtain the red spectrum the strength of the current must be adapted to the gas pressure. Kayser employed an induction coil. The condenser, however, in the primary of an induction coil sends an oscillatory discharge through the secondary. Although Kayser did not employ a condenser in the manner recommended by Crookes, he still had a condenser in his electrical system and the resistance of his Geissler tube was probably so proportioned that the secondary circuit was in resonance with the primary circuit. To prove this we placed a tube containing argon across the terminals of the secondary of an induction coil, and having removed the condenser attached to the primary, we sent the discharge through the tube by means of a break in the induction coil. The light of the discharge was red, and when it was examined by a revolving mirror no trace of blue was seen in the capillary portion of the tube. An adjustable condenser and a variable induction were then placed in the primary circuit. By varying the amount of the capacity together with the self-induction in the primary system, the discharge in the secondary, when examined by a revolving mirror, was seen to consist of both red and blue discharges. The red glow was evidently due to a unidirectional discharge and the blue to an oscillatory discharge. The unidirectional discharge was caused by the failure of the breaks to charge the condenser to the primary, or by increased resistance in the tube. When, however, the condenser was charged, it immediately discharged in an oscillatory manner; and the secondary coil responded by resonance. The rarified argon thus shows in an interesting manner what is the function of the condenser in the primary of an induction coil. It serves to send oscillatory discharges through the primary circuit; and the greatest effect is obtained in the secondary circuit when it is in resonance or in tune, so to speak, with the primary.

The presence of a condenser was necessary to form the blue glow in Kayser's work, only when the resistance of his tube and the self-induction of his coil together were enough to damp the discharge of the small capacity of the coil. He could have obtained the pure red in any case by interposing, as we have done, a resistance or self-induction between the condenser and the tube, although our other resource for obtaining

* Sitzungsberichte der königlich preussischen Akad. der Wissenschaften zu Berlin, May 7, 1896.

the red glow in any tube from the continuous discharge of a constant battery was apparently not open to him.

By taking out all resistances except the spectrum tube, and sending an exceedingly strong current through the tube for very brief intervals of time, we have been able to cause the blue glow; but it seems probable that under these conditions the capacity of the battery itself engenders oscillations which are no longer damped by interposed resistance. Whether the blue glow with its accompanying change of spectrum is due merely to the great quantity of electricity discharged in a very short space of time, or to some property intrinsic in the to-and-fro motion of the oscillatory discharge, is a question, which we hope soon to answer. The red glow, if caused by oscillations at all, must be caused by oscillations within the Geissler tube itself;* for all outside oscillations are cut off by the large resistance between the battery and the tube.

The effect of the oscillatory discharge in producing the blue spectrum of argon can also be shown by the use of an electrical machine. If the terminals of the tube containing argon are connected with the terminals of an electrical machine, the pure red spectrum is obtained. If a spark gap is interposed in such a manner that a condenser charged by the machine can discharge through the tube, the blue discharge immediately results. The condenser discharge oscillates through the gas.

The oscillatory discharge of the condenser is evidently an important factor in producing the blue spectrum of argon. According to Lord Kelvin's law, if R denotes the resistance of the circuit, L , the self-induction, and C the capacity of the circuit, the discharge of the condenser becomes non-oscillatory when $R = \sqrt{\frac{4L}{C}}$. It may be, therefore, that an estimate of the

resistance in the tube can be obtained by measuring the self-induction which is required to change from the blue discharge to the red.

When the tube containing argon at a suitable pressure is brought near a Hertz oscillator, giving a rate of about 115,000,000 oscillations per second, it immediately shows the blue color. In this case the oscillator consisted of two zinc plates about 40^{cm} square with a spark gap between them. The capacity and impedance of the circuit was extremely small.

The unusual sensitiveness of an argon tube to oscillatory discharges leads us to believe that it will be of great use in the study of wave motions of electricity. As we have seen, it is competent to show when the Hertz oscillator is working properly, that is, sending forth electrical oscillations and not unidi-

* *Ann. der Physik und Chemie*, 1893, vol. xlviii, 549, Ebert and E. Wiedemann.

rectional discharges. The change of color in the tube from red to blue is so marked that an argon tube reveals what is not shown in a conspicuous manner by other gases. We have thought that this remarkable property of an argon tube is worthy of being distinguished by a name which might describe it and we have, therefore, called an argon tube fitted for the study of electrical waves a talantoscope (*ταλάντωσις*).

In an oscillatory discharge the molecules receive powerful electrical impulses of opposite sign. These impulses are separated, it may be, by millionths of a second. It is significant that the shorter wave lengths of light accompany these electrical oscillations. It is our purpose to extend our study of the effect of electrical oscillations through more highly rarified media in which arise the Röntgen rays. These rays are probably highly modified by the oscillatory discharge. A battery of a large number of cells now at our command will afford the best means of studying this subject: for its discharges, as we have pointed out, are free from the fluctuating effects produced by induction coils, transformers and electrical machines. Our present paper is, therefore, only preliminary to a more exhaustive study of the discharges of electricity through rarified gases, by means of a storage battery of ten thousand cells, which will give an electromotive force of about twenty thousand volts.

Harvard University, Dec. 1st, 1896.