POST-ARC CONDUCTIVITY AND METASTABLE HELIUM

By Carl Eckart

Abstract

Conductivity of helium immediately after arcing through it.—A study has been made of the abnormal conductivity which Kannenstine found persisted for .007 sec. after the arc was extinguished. The results prove that the residual conductivity is due to positive ions and not to metastable excited helium atoms, as suggested by Kannenstine. By means of adjustable commutators, the arc tube was connected first to a battery which caused an intense arc (period A), then after a brief interval (period B) to a source of voltage V_c through a micro-ammeter (period C). As V_c was increased the micro-ammeter showed a small negative current (positive ion) to 1.2 v., then a regularly increasing positive current reaching saturation at 8 v. The logarithm of the saturation current was a linear function of the length of period B for $V_c = -15$ v. and for $V_c = -26$ v., the current decreasing to one tenth in from .004 to .007 sec. (*Similar observations in mercury* gave a constant of .01 to .02 sec.). Observations with a Braun tube oscillograph gave direct additional evidence that after the arc ceased, the current decreased exponentially with time, independent of the length of the interval B. An attempt to sweep the positive ions away by applying a high negative voltage during B failed. Spectrographic observations made with a rotating slit attached to the commutator showed that no light was emitted during period C, even when the helium had been so carefully purified that the bands were distinctly visible in the spectrum of the arc.

Life of metastable helium (states 2S and 2s).—While there is good evidence that metastable helium atoms persist for a longer time than ordinary excited atoms, the only evidence for a life of the order of 1/140 sec. rests on Kannenstine's interpretation of the persistent post-arc conductivity, and the experiments in this paper prove his interpretation to be unjustified.

Introduction

SOME of the most interesting developments in the study of the atom, center about the so-called metastable states. The valence electron of an atom in such a state moves in an orbit whose energy is greater than that of the normal orbit, but a reversion from this orbit to the normal with the emission of radiation is forbidden by the selection principles. The length of time that the atom persists in a metastable state will presumably be longer than for the ordinary excited state, for the ordinary excited state is terminated by the emission of a quantum of radiation, a process which is usually determined primarily by the internal mechanics of the atom. The energy of the metastable state, however, cannot escape from the atom without the co-operation of some external agent, most likely another atom, and a process involving two atoms is much less probable, other things being equal, than one involving a single atom.

Franck and Reiche[1] used this hypothesis of a long life to explain certain absorption phenomena observed by Paschen in helium. The hypothesis has since been supported by a variety of observations on helium, mercury, and other elements; but estimates of the actual duration of the metastable state are by no means consistent. Indirect evidence points to a life of the order of 10^{-6} or 10^{-5} sec. for metastable helium, while an apparently very direct determination by Kannenstine[2] gave 1/140 sec. In the case of mercury, the lower limit is about the same, and the upper value, due to Marshall,[3] using Kannenstine's method, is 1/22 sec. It is the purpose of this paper to determine whether the larger values given by Kannenstine's method are reliable.

The method employed by Kannenstine was first suggested by Franck and Reiche and is based on the following considerations. If helium is bombarded by 20 volt electrons, a large proportion of the atoms are thrown into the metastable state. The atoms in this state can be ionized by the impact of a 4 volt electron. Consequently, if the potential accelerating the bombarding electrons is suddenly reduced from 20 v. to 4 v., the current flowing should be abnormally high until all the excited atoms are ionized or disappear due to other causes. The duration of this abnormal post-arc conductivity was therefore taken by Kannenstine and Marshall as a measure of the life of the metastable atom.

However, under the conditions of the experiment the concentration of positive ions in the gas is comparable with, if not very much greater than, the concentration of metastable atoms. Further, the life of an ion may be expected to be comparable with the life of a metastable atom. It therefore becomes necessary to show that the abnormal currents are not due to ions formed during the arc period, rather than to ions formed from metastable atoms during the post-arc period.

Experimental Procedure and Results

1. Kannenstine's experiments were repeated, using a more sensitive means of measuring the post-arc conductivity. A commutator[4] was used which connected the arc tube to a source of 30 to 60 volts d.c. for a certain time interval (period A) determined by the speed of the shaft. This caused an intense arc. During a shorter time interval (period B) immediately following, the arc tube was disconnected from any source of current. The length of this period could be varied independently of period

[1] Franck and Reiche, Zeits. f. Phys. **1,** 154, 320 (1920).
[2] Kannenstine, Astrophys. Jour. **59,** 135 (1924).
[3] Marshall, Astrophys. Jour. **60,** 142 (1924).
[4] I wish to thank Professor E. P. Adams for the use of this apparatus.

A. Then, during a third interval (period C), the arc was connected through a micro-ammeter to another source of voltage V_c. The connections during the three periods are shown in Fig. 1.

The micro-ammeter thus read the time average of a current which was zero except during period C. For some experiments, the micro-ammeter was replaced by a galvanometer.

If the post-arc conductivity is due to the ionization of excited atoms, then for V_c less than about 4 v. (the ionizing potential of the metastable atom) only the current due to electron emission from the cathode should

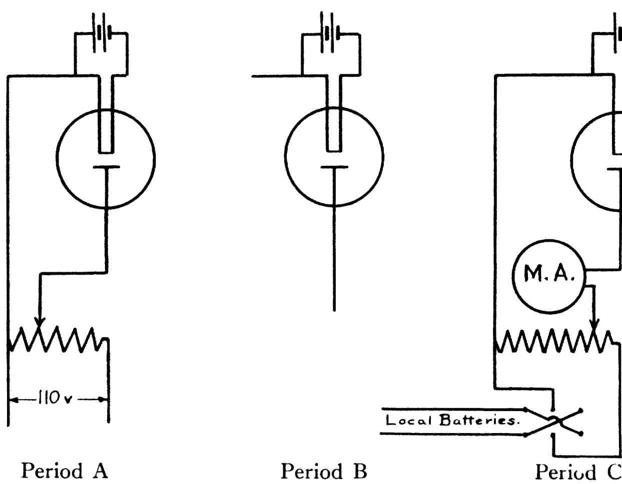

FIG. 1. Connections during each of the three periods.

be observed. At $V_c = 4$v., the current should begin to rise rapidly, possibly approaching a limit for voltages greater than 4 but less than the first excitation potential of normal helium.

The actual relation between current and voltage during period C is shown in Fig. 2, which is typical of a large number of runs. For voltages less than 1 v., the current was negative, i.e., of opposite sign to any possible thermionic current. It may be remarked immediately that this current was much too large (10 to 50 micro-amp.) to be photoelectric in origin. The only possible explanation is that it was due either to a large supply of positive ions in the tube, or to reactance in the external circuit. As V_c was increased from 1 to 3.5 v., the current increased very rapidly. Further increase in V_c produced an additional increase in current, but a saturation value was soon reached. The current then remained constant to within a few percent until the first excitation potential of the normal atom (20 v.) was reached. It is to be noted that the ratio between this saturation current and the positive ion current is of the order of magnitude of $\sqrt{M/m}$ where m is the mass of the electron and M of the positive helium ion.

In various runs, current readings were taken at small voltage intervals from 1 to 8 v. The results were plotted in various ways which would have accentuated any change in the functional relationship between I and V_c. The only changes observed were gradual ones, resembling those found in the current-voltage relationship of the Langmuir exploring electrode[5] much more nearly than those due to critical potentials.

To make certain that no spurious reactance effects were causing these currents, the voltage during period A was reduced from 30 v. to 23 v.,[6] at which value the arc no longer struck. If the currents during C were due to capacitance, they should be reduced in approximately the ratio

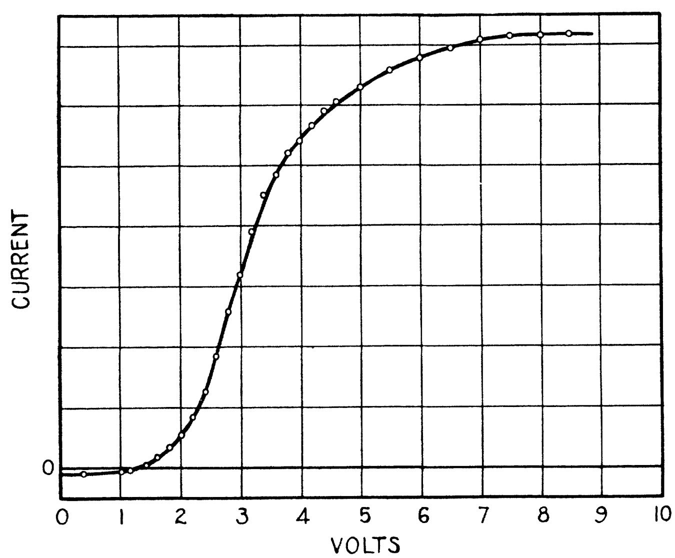

FIG. 2. Relation between current and voltage during period C. Period A = .0045 sec.; period B = .0008 sec.; period C = .0045 sec.

23:30. Actually, under these conditions, only the normal thermionic current could be obtained. Then the arc tube was replaced by a non-inductive resistance, and the voltage during period A adjusted so that the current flowing was about the same as that flowing under the conditions of Fig. 2. The current during period C was now approximately

[5] Langmur, Gen. Elec. Rev. **26,** 713 (1923); Langmuir and Mott-Smith, Gen. Elec. Rev. **27,** 444, 538 (1924).

[6] These voltages have not been corrected. They are the readings of a voltmeter which was continuously connected across the potentiometer (Fig. 1). As the arc was connected to the same terminals only during a fraction of the time, the readings are considerably higher than the actual voltage across the arc-tube when it was drawing current.

proportional to V_c and independent of the speed of the commutator, indicating that inductance effects were negligible.

2. In order to determine the rate of decay of this post-arc conductivity, period B was varied while periods A and C were kept constant. This was possible because the segments of the commutator that made contact during period A were on a separate drum from those that made contact during period C. These two drums could be rotated relative to each

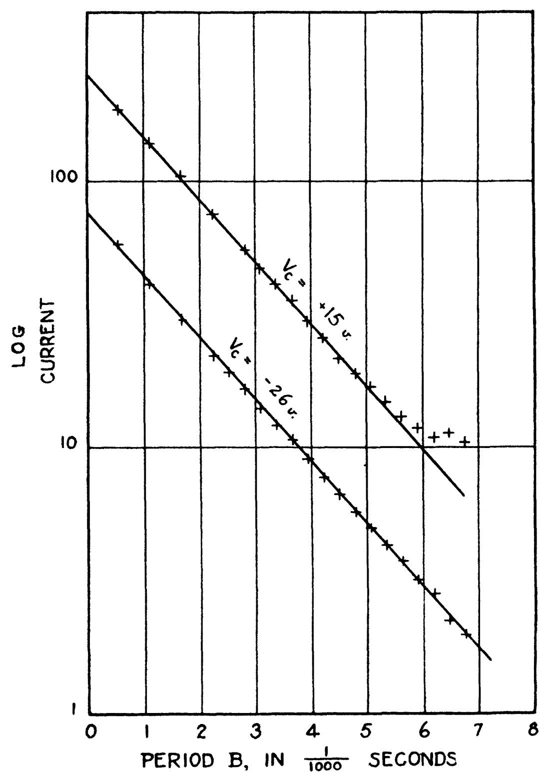

FIG. 3. Variation of average current during period C with the length of period B. Period A = period C = .014 sec. The ordinates of the two graphs are not comparable.

other and then fastened to the shaft with set screws. The angles corresponding to the three periods having been determined, a measurement of the speed of the commutator furnished the remaining datum for calculating their actual lengths in seconds.

For each length of period B, two current readings were taken, one at +8 v. and one at −20 to −30 v. The results of a run of this kind are shown in Fig. 3, where the logarithm of the current is plotted against the length of period B. It is very remarkable that the graphs thus obtained should be linear, and even more remarkable that the points for positive currents should lie on a line which is almost exactly parallel to the line for the negative currents. This indicates that the positive currents are proportional to the negative currents. So simple a relation would not be expected if the positive currents were determined by an entirely different mechanism from that determining the negative.

Not all of the runs showed this proportionality as distinctly as Fig. 3, but an explanation of this will be given below. However, the negative currents could almost always be represented by an equation of the form

$$I = K\ (10)^{-t/b} \tag{1}$$

where t is the length of period B in seconds. For helium, all values of b which were observed ranged between .004 and .007 sec. If it is assumed that Kannenstine's apparatus could no longer detect the abnormal conductivity after it had fallen to, say, 1/20 of its original value, the agreement with his result of 1/140 sec. is very satisfactory.

Some hasty experiments using mercury instead of helium showed that all phenomena were essentially the same and yielded values for b of .01 to .02 sec. Marshall's value of 1/22 sec. is again in good agreement.

3. The foregoing experimental method has the advantage of high accuracy, but the disadvantage that it yields only average values of the post-arc conductivity. Kannenstine's use of a Braun tube oscillograph enables instantaneous values of the current to be obtained. Accordingly, a Braun tube was introduced into the circuit so that it indicated the current during all three periods. The spot was given a uniform horizontal motion across the screen by discharging a condenser in synchronism with the commutator through a thermionic valve. The vertical deflection, proportional to current, was obtained either by magnetic or electrostatic deflection. In the latter case, the current was passed through a non-inductive resistance, shunted across the deflector plates.

In Fig. 4 are shown tracings of photographs of the Braun tube figures. The regions corresponding to the three periods are marked. Conditions during periods A and B were not varied, but the voltage across the tube during period C was given the various values indicated. When V_c was 1 v., the current was too small to be indicated (instantaneous values probably less than 15 micro-amp.). At 1.5 v. the current was still small, but definitely noticeable. As V_c increased from 1.5 to 3.5 v. (the region of rapid increase of current, Fig. 2) the type of figure did not change. The current rose gradually from zero to a value determined by the voltage, and then remained constant until the end of the period.

At $V_c = 4$ v., the type of figure began to change. The current rose to a maximum and then diminished again, the shape of the curve suggesting strongly that it could be represented by an equation of the form

$$I = Ke^{-t/a}(1 - e^{-t/c}). \quad (2)$$

When V_c was increased beyond 8 v., the shape and size of the figure remained constant.

When the currents were increased by raising the filament temperature, a transition stage (Fig. 5a) became clearly distinguishable. This stage was especially marked when the speed of the commutator was reduced, so that period C was long. The presumption is that stages *bcd* of

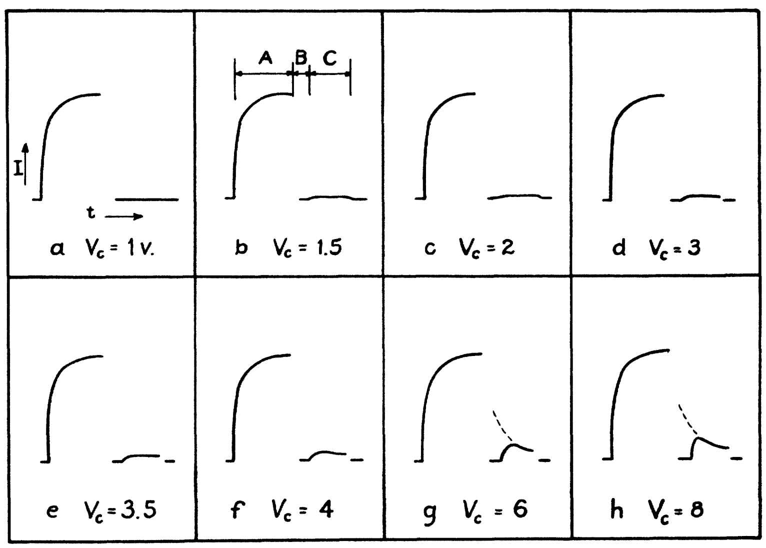

Fig. 4. Tracings of photographs of Braun tube figures.
Period A = period C = .002 sec.

Fig. 4 are really identical with that of Fig. 5a, but that period C ended before the decrease in current became apparent. Furthermore, under certain conditions it was impossible to pass beyond this stage even when V_c was made as high as 10 v. The value 4 v. at which the type of figure begins to change in Fig. 4, has thus no significance.

These results show beyond doubt that the post-arc currents are limited by more than one cause. Some indication of the probable character of these causes may be obtained from the two experiments now to be described. In the first the arc tube was replaced by a non-inductive resistance of about 1000 ohms. A voltage was applied through the commutator and the current-time curve obtained with the Braun tube. The current rose to a constant value in what appeared to be an exponential fashion, as was to be expected. The time required for the constant value to be reached was of the same order of magnitude as that occupied by the convex portion of the curve during period C in Figs. 4 and 5a. The presumption is, therefore, that the factor $(1-e^{-t/c})$ in Eq. (2) is introduced by the reactance of the circuit, and is not indicative of any change within the tube.

In the second experiment, the arc-tube was again placed in the circuit, and a photograph of the Braun tube figure taken under the conditions of Fig. 4,(h). Period B was then lengthened considerably, nothing else being changed, and the resulting figure superposed on the previous exposure. A tracing[7] of the plate obtained in this way is shown in Fig. 5b. This result must be interpreted to mean that the convex portions of the curves in Figs. 4 and 5a are determined by phenomena inside the tube, *and that these phenomena are independent of the amount of electricity which has passed through the tube.* In other words, the value of the factor

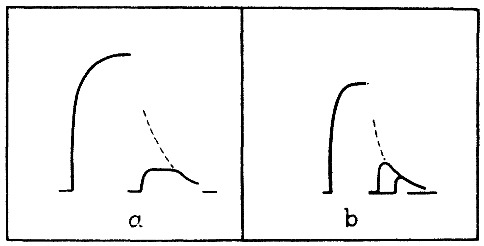

Fig. 5a. Braun tube figure showing transition stage with higher current.
Fig. 5b. Braun tube figures for $V_c=8$ and for two lengths of period B.

$Ke^{-t/a}$ in Eq. (2) is determined entirely by conditions inside the tube at the end of period A, and not at all by the length of period B. In the method of section 2, this factor is obviously the one which will affect the micro-ammeter reading most strongly. The linearity of the upper graph of Fig. 3 is thus explained, if we assume that the readings were taken under the conditions of Fig. 4 (h). The fact that these graphs were not always linear is explained by Fig. 5a. If the readings for Fig. 3 had been taken under these conditions, no straight line would have been obtained.

No satisfactory explanation has been obtained for the horizontal portion of Fig. 5a, though an interesting hypothesis has suggested itself, which is reserved for further experimental consideration. For the present, it will merely be remarked that Kannenstine and Marshall apparently performed all their work under the conditions of this figure.

Returning to the discussion of Fig. 5b, it must be interpreted to mean that nothing inside the tube is used up by the passage of current during

[7] On the original plate, the lines were very much less definite than in the tracing. There is no doubt, however, that the relation is essentially as drawn in Fig. 5b.

period C. This is not what would be expected if the abnormal conductivity were due to the ionization of metastable atoms. If the large currents are due to the neutralization of negative space charge by positive ions already present, however, this result is quite explicable, for the velocity of the positive ions under such low fields would be very small, and only a very small portion of the total current would be carried by them. Furthermore, there is good experimental evidence that positive ions disappear by recombination with electrons at the walls of the tube and relatively only slowly by recombination in the body of the gas.

Some portions of the theory outlined in this section are possibly more detailed than is justified by the amount of experimental evidence presented and should be considered as merely provisional. It has been shown, however, that the hypothesis that persisting positive ions are the cause of the abnormal post-arc conductivity is better capable of explaining some of the phenomena than is the metastable helium hypothesis of Kannenstine.

4. Several crucial experiments are suggested by the above theory. If the current during period C is determined by positive ions which are in the tube during the entire period B, it is to be expected that the application of a high negative voltage across the electrodes during period B would sweep them out of the tube, and thus materially alter the conductivity during C. Accordingly, a commutator was constructed by means of which it was possible to perform this experiment. The two drums which determined periods A and C each had four contacts. A third drum had only two, shorter contacts. This drum was oriented so that it made contact with its brushes during alternate intervals between A and C. In this way it was possible to obtain simultaneously on the Braun tube screen the figures corresponding to two different sequences of periods: ABC and AB′C. ABC was the sequence previously used (see Fig. 2); AB′C was the same except that during B′ the arc-tube was connected to a third source of voltage.

With this apparatus, the experiment of Fig. 5b could be repeated with great ease by merely making the voltage during B′ the same as that during C. The comparison of ABC with AB′C was visual and instantaneous. No double photographic exposure was necessary.

When the voltage during B′ was made negative, however, it was found that this had little or no effect on the current during C. This was the case, even when a negative voltage of -135 was applied. This result is somewhat disconcerting, but may probably be explained by the shortness of the interval during which the negative voltage could be applied. It is also possible that the potential gradient set up inside the tube was not as great as would be indicated by the applied voltage. This would be the case if a positive ion sheath were formed over the anode, which Langmuir[5] has shown to be the case when an electrode at a very negative voltage is introduced into a region of intense ionization.

5. A further possibility of distinguishing between the two hypotheses is to be found in the mechanism of the disappearance of positive ions discussed above. If the currents during C are due to the persistence of actual ions, no spectral emission will be expected during this period, even though the current flowing is quite large, but if ionization of excited atoms is the cause of the conductivity, then the spectral emission during C should be comparable to that during A, since the currents flowing are comparable.

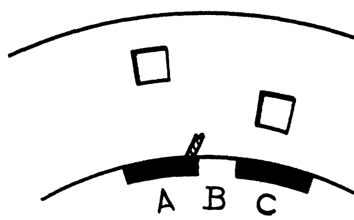

Fig. 6. Diagram showing relative position of perforations in disk and of the commutator segments.

In order to compare the intensity of the spectrum during the two periods, a perforated disk was mounted on the same shaft as the commutator. This is shown diagrammatically in Fig. 6. The disk contained two sets of perforations, and an image of the arc was thrown on it by a large RR objective in such a way that one portion of the image was exposed by one set of perforations during period A, while a symmetrical portion was exposed by the other set during period C. The electrical circuits and the speed of the commutator were then adjusted so that the current during period C was one quarter to one third that during A. Observation showed an intense visible discharge during A but no trace of spectrum during C.

A comparison of the spectral intensities was made with a small Hilger spectrograph. The stronger helium lines were visible on the portion of the plate exposed during period A when the exposure time was three minutes. They were not visible on that part exposed during period C, even when the exposure time was increased to 20 minutes.[8]

[8] It should be noted that these experiments do not indicate that the spectrum disappears instantaneously when the voltage is removed, but merely that it does not persist as long as the post-arc conductivity. What bearing this result has on the work of Webb and (Miss) Hayner (Phys. Rev. **23,** 294, 1924; **26,** 364, 1925) is not obvious.

6. The helium band spectrum is an excellent indicator of the concentration of metastable atoms built up during the discharge. Consequently, if the post-arc currents are due to metastable atoms, their intensity should vary with the intensity of the band spectrum.

All of the experiments so far described were performed with helium which would ordinarily be called pure, but this helium showed no trace of the band spectrum when the discharge was passed through it at the pressure (3 mm) used. The helium was now treated by a method used by Paschen[9] to remove sub-spectroscopic traces of impurity. A small amount of electrolytic oxygen was admitted into the arc tube containing the helium, and the arc discharge was then allowed to run until the oxygen spectrum was no longer visible. After two such treatments the band spectrum appeared with considerable intensity. The lines were identified with a Hilger direct reading spectrometer. The characteristic yellow band, shading off toward the violet, was distinctly visible. While the helium was in this state of purity a number of the previous experiments were repeated, but no differences in the results could be detected with certainty. In particular, no spectrum was observed during period C under these conditions.

Conclusions

1. The only experimental evidence in favor of a very long life (10^{-3} to 10^{-2} sec.) of metastable atoms rests on the assumption that the abnormally high conductivity of helium immediately after a discharge has passed through it is due to the presence of metastable atoms.

2. It is shown that the evidence is not in favor of this assumption, but that the abnormal conductivity is due to the persistence of actual positive ions, and accompanying electrons.

3. That the metastable states ($2S$ and $2s$) in helium have a longer life than other excited states is not questioned by this work but that their life is as long as has been stated by Kannestine ($^1/_{140}$ sec.) is shown to be untrue.

I wish to thank Professor K. T. Compton for his constant and helpful interest in this work, and the Board of Directors of the Edison Lamp Works for their generous support of a fellowship which made the prosecution of this research possible.

Palmer Physical Laboratory,
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May 4, 1925

[9] Paschen, Ann. der Phys. **45,** 625 (1914).