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Secondary Electron Emission by Photoelectric Action and Ion Bombardment at the Cathode in Corona Breakdown of Argon

LAURA COLLI* AND UGO FACCHINI*
Department of Physics, University of California, Berkeley, California
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Differences between the secondary cathode mechanisms active in coaxial cylindrical argon-filled counter tubes with positive central wire at various gas pressures observed by E. J. Lauer at Berkeley and the authors at Milan, have been resolved as a result of recent work by the authors at Berkeley. It appears that at pressures ranging from 1000 to about 150 mm Hg, with spectroscopically pure argon, the dominant mechanism is a photoelectric liberation from the cathode caused by photons with some microseconds of time delay and of energy about 10 ev. These lead to a corona threshold with γ_p ranging from 1 to 5×10^{-3}, uncorrected for electron back diffusion. At pressures between 25 and 100 mm Hg an electron liberation by impact of A^+ and A_2^+ ions on the Ni cathode was confirmed to be important in the corona current, in agreement with Lauer's findings. This effect seems to be very dependent on the conditions of the surface and was found to be active only after a degassing at 900°C for hours.

A NUMBER of papers have been published in recent years on the mechanisms of production of secondary electrons which take place in the electrical breakdown in argon, either in a plane parallel geometry or in cylindrical geometry.[1–7] These studies were carried out under varying conditions and revealed different aspects of the mechanisms involved.

Because of notable differences between the results obtained at Milan[5] and at Berkeley,[4] and through the courtesy of the Fulbright Award Committee and the U. S. Office of Naval Research, it became possible for the authors to extend their investigations in the laboratory of Professor L. B. Loeb in the Physics Department of the University of California at Berkeley. The purpose of this note is to report and analyze critically the results obtained with positive wire coaxial cylindrical geometry at both places and to show how the results can be brought into agreement and the differences explained.

In the first Milan paper,[1] the action of a photoelectric effect at the cathode was observed, by analyzing the shape of α-particle pulses in the pre-corona amplification region. However, in that work, the argon purity was not satisfactory and the impurities contained in argon (about 10^{-3} parts of CO_2) seriously influenced the results.[8] Subsequently, and independently, two studies were carried on, by the authors in Milan[5] and by Lauer in Berkeley,[4] utilizing the same method and with argon of high purity. In the next sections we will discuss these studies, which will be denoted in what follows as M and B, respectively.

THE PHOTOELECTRIC EFFECT; RESULTS AT MILAN

The cathode tube used was of brass, 6 cm in diameter, and was outgassed at 200°C. Argon of initial purity 98 to 99.9 percent was introduced into the discharge tube and circulated over a Ca-Mg alloy, heated to 450° for purification purposes. The pressures which were found convenient for study ranged between 150 and 1000 mm Hg. In a further unpublished study at Milan, the same measurements were repeated using a nickel cathode 5 cm in diameter, outgassed to 350°C, with no change in results.

The results which are of significance for this discussion can be summarized as follows:

* On the staff of Laboratori C.I.S.E., Via Procaccini 1, Milan, Italy.
[1] Colli, Facchini, and Gatti, Phys. Rev. **80**, 92 (1950).
[2] J. A. Hornbeck, Phys. Rev. **83**, 374 (1951).
[3] J. P. Molnar, Phys. Rev. **83**, 933, 940 (1951).
[4] E. J. Lauer, J. Appl. Phys. **23**, 300 (1952), referred to as B in the text.
[5] L. Colli and U. Facchini, Phys. Rev. **88**, 987 (1952), referred to as M in the text.
[6] L. H. Fisher and G. A. Kachickas, Phys. Rev. **91**, 775 (1953).
[7] R. N. Varney, Phys. Rev. **93**, 1156 (1954).
[8] Colli, Facchini, and Gatti, Phys. Rev. **84**, 606 (1951).

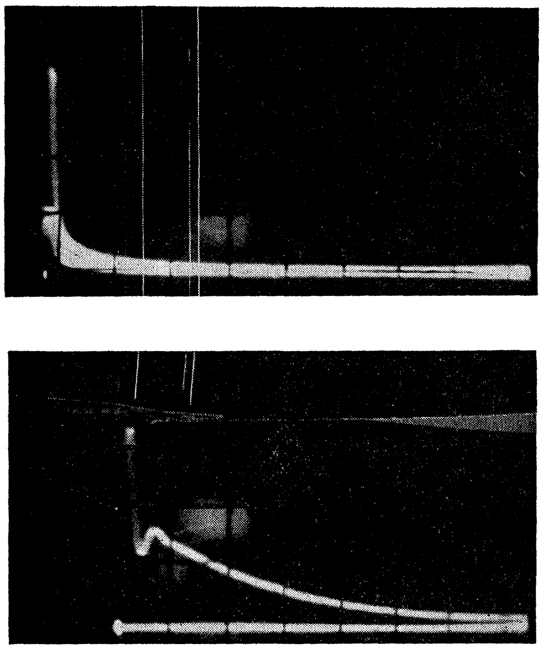


FIG. 1. α-particle pulses. Experimental conditions as in B. Cathode: nickel well outgassed, 2.9 cm in diameter; argon pressure: 400 mm Hg; corona threshold: 1660 volts; sweep time: 100 μsec. The upper pulse, taken 100 volts below the corona threshold, shows the electronic shape of the primary avalanche with no secondary effect. The lower pulse, taken at the corona threshold, shows the peak and the continuous slope due to the diffused photoelectric effect.

1. The corona current is due, mostly, to a secondary photoelectric effect produced at the cathode by photons generated in the Townsend avalanches near the wire. This statement is supported by the shape of α-particle pulses observed just below the corona threshold (see Figs. 4–7 in M).

2. The Townsend multiplication coefficient at the corona threshold, N_s, has a value of 200–300 with the various pressures and surfaces used. Denote by γ_p the number of photoelectrons extracted from the cathode and reaching the wire for each electron present in the Townsend avalanche. The values of γ_p are determined from the well-known equation, $N_s\gamma_p=1$, at corona threshold.

From the data γ_p was evaluated as $\gamma_p \simeq 3\text{–}5\times10^{-3}$, not very dependent on the pressure used, and it appeared to be of the same order of magnitude for nickel and brass.[9]

3. The α pulses near the corona threshold at pressures over $\sim$300 mm Hg, were followed by a convergent succession of pulses corresponding to the successive avalanches produced by photoelectrons. The successive pulses were diffused in time and the diffusion became greater as the pressure decreased, until at pressures below 300 mm Hg the successive avalanches overlapped to a continuous slope following the α primary pulse.

To explain this effect, it was assumed that the active photons were produced during a period of the order of few microseconds which increased as the pressure decreased.

THE DELAYED PHOTON PRODUCTION

In a recent paper, one of us[10] directly studied the time of production of the photons and established their energy as about 10 ev. It was found that in a Townsend avalanche lasting less than 5×10^{-7} sec, photons are emitted obeying the law $[\exp(-9p^2t)-\exp(-3\times10^5t)]$, which gives the emission rate *versus* time, with p the pressure in mm Hg and t the time in seconds. This law corresponds to a photon burst with a rise time of about 1 μsec and a delay time of 3.4 μsec at pressures above 300 mm Hg, and to a burst with both the rise time and the delay time longer at lower pressure. In that paper, it was suggested these photons might be produced by the decay of excited argon molecules A_2^*, formed by metastable atoms in three-body collisions. These results furnish a satisfactory explanation of the γ_p pulse shapes mentioned in the previous section.

THE PHOTOELECTRIC EFFECT; RESULTS AT BERKELEY

Turning to the appropriate sections of the paper B, it should be noted that the cathode used was nickel well outgassed by electron bombardment and with a diameter of 2.9 cm. Spectroscopically pure argon was directly introduced in the discharge tube, at a pressure ranging from 25 to 400 mm Hg. In this work, the action of an ion cathode γ_i effect was observed. The α-particle pulses near the corona threshold were followed by secondary pulses at time intervals of 100–600 μseconds depending on pressure corresponding to the ion transit-time across the gap. The values of γ_i (number of electrons extracted from the cathode per incident ion), were found to be about 10^{-3} at the lower pressures ($\sim$100 mm Hg), and much smaller at higher pressures, i.e., 6×10^{-5} at 200 mm Hg and 2×10^{-5} at 600 mm Hg. At these pressures, the values of N_s (threshold multiplication), were found about 400 to 600.[11]

DISCUSSION OF BERKELEY RESULTS

It appears, at pressures above 200 mm Hg, that $N_s\gamma_i \ll 1$, and that this secondary ion process could not have been responsible for the corona current at threshold. The most probable explanation was that the diffused photoeffect observed in M, was responsible for the corona mechanism in the B study as well. The tube used in B had a diameter of 2.9 cm, smaller than the one used in M, and consequently the transit time of electrons in B was 2–3 microseconds instead of 6–8

[9] A decrease in γ_p of roughly a factor 2 was noted after the outgassing at 350°.

[10] L. Colli, Phys. Rev. 95, 892 (1954).
[11] E. J. Lauer (private communication).

microseconds as in M. It is therefore to be expected that in a counter such as used in B the successive avalanches, even at a pressure of 400 mm Hg, completely overlapped

RECENT EXPERIMENTAL VERIFICATION

When the authors undertook a study at Berkeley of the α-particle pulses at an appropriate sweep rate with the apparatus used in B, at pressures of 400 and 200 mm Hg, Figs. 1 and 2 were obtained, which are in good agreement with the assumptions made. Under the assumption that the photoeffect is the most important effect acting above 200 mm Hg from the values of N_s, found in B, the values of $\gamma_p \simeq 1.5\text{–}2.5 \times 10^{-3}$ were obtained, in good agreement with the ones found in Milan.

ION CATHODE EFFECT

At pressures between 25 and 100 mm Hg, the values of $N_s\gamma_i$ found in B are of the order of $\frac{1}{2}$ and the ion-cathode effect plays an important role in the corona current. However, in M, the ion-cathode effect was not observed. It must be noted that the lowest pressure used in M was 150 mm Hg. Recently much work has been done by Hagstrum[12] and by the Berkeley group[13] on the extraction of electrons from metals bombarded with ion beams under conditions of high purity and outgassing techniques. Hagstrum used a beam of helium ions having energies between 10 and 1000 ev against "flashed" surfaces of Mo, Ta, and W. Parker[13] studied, among others, argon ions with energy between 2 and 150 ev against "flashed" surfaces of Ta and Pt. It was found by Hagstrum and confirmed by Parker[13] and Huber[14] that γ_i is generally strongly dependent on the surface conditions; particularly Parker, with argon ions of low energy, found a reduction in γ_i by a factor of 10 or so when the surface was covered by a molecular gas layer. Hagstrum also observed that the complete cleaning of the surface is not achieved by heating it in vacuum up to 500°C, but only by heating the target above 900°C. After cooling, the gas layer reforms in a time dependent on the residual gases pressure and on the metal considered. It varies, for instance, from seconds at a pressure of 10^{-6} mm Hg with tungsten to hours under better conditions. The gas layer is also quickly reformed when the clean surface is exposed to a noble gas containing small amounts of molecular impurities. These results readily explain the failure to observe a γ_i effect in M. In fact, (1) the brass and nickel used there were outgassed only to 350°C; (2) argon which was not completely purified was introduced into the tube, the purification requiring a few hours of circulation over Ca-Mg. It must be concluded that the cathode surface was thus not very clean but covered by a thick gas layer and consequently the γ_i values expected should have been less than those observed in B, taken with a more thoroughly outgassed surface. In this connection, it is of importance to note the observations made on a nickel surface contaminated in the course of the recent studies with the apparatus used in B. The nickel surface was initially outgassed ten hours at orange-red heat (900 to 1000°C), and after cooling in good vacuum was exposed for a few hours to spectroscopically pure argon. It then showed a nice succession of γ_i pulses at 50 to 100 mm Hg. On the other hand, if the same cathode was exposed for a few minutes to air or to 99.5 percent pure argon, the gas being subsequently removed and the tube filled with the spectroscopically pure argon the γ_i pulses then completely disappeared. With such contamination, the threshold voltage is increased about 20 volts and the threshold multiplication by a factor 2 or so. Under these conditions the photoelectric effect appeared to be the most important action. In fact, γ_p appeared to be little altered by the surface treatment. It is interesting to note that the photoelectric emission from surfaces does not parallel the ion bombardment emission and may vary in quite different fashion with the surface conditions.[15,16]

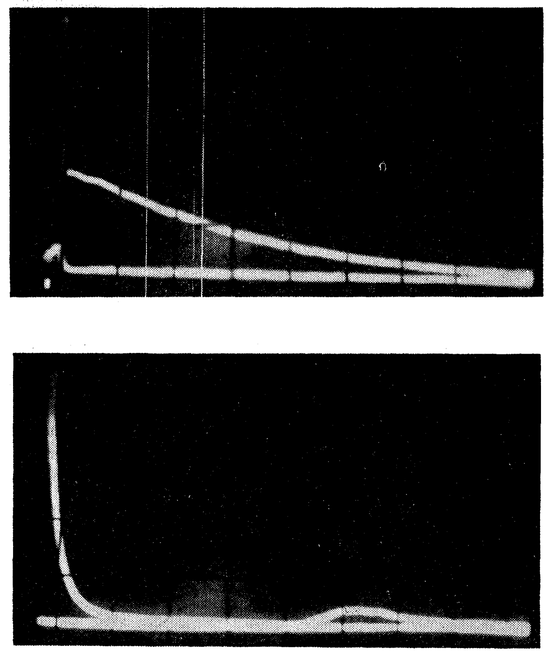


FIG. 2. α pulses at the corona threshold. Experimental conditions as in B. Argon pressure: 200 mm Hg; corona threshold: 1265 volts. The upper pulse, taken with a sweep time of 100 μsec, shows the diffused photoelectric effect following the primary avalanche. In the lower pulse, taken with a sweep time of 1300 μsec, it is possible to see the primary avalanche, the following slow photoeffect, and also the secondary peak at about 600 μsec due to the ion-cathode effect. At this pressure, the ion-cathode effect is estimated to be of the order of few percent of the photoelectric effect.

[12] H. D. Hagstrum, Phys. Rev. **89**, 244, 338 (1953); **91**, 543 (1953).
[13] J. H. Parker, Phys. Rev. **93**, 1148 (1954).
[14] E. Huber, Ph.D. thesis, University of California, June, 1954 (unpublished).
[15] Wainfan, Walker, and Weissler, J. Appl. Phys. **24**, 1318 (1953).
[16] Barch, Irick, and Geballe, Sixth Gaseous Electronics Con-

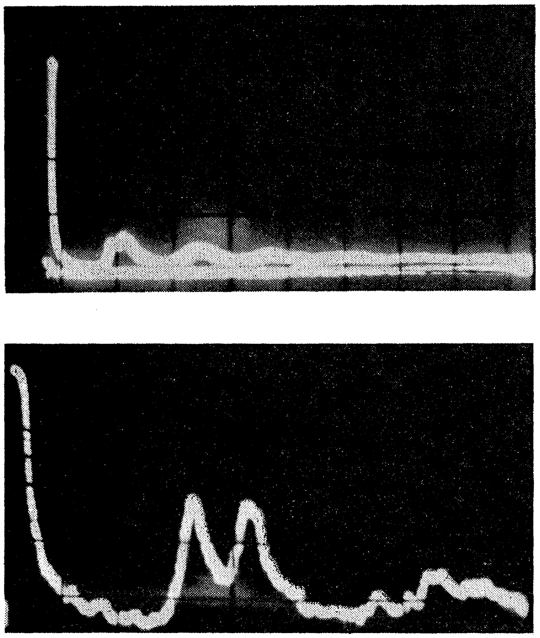


FIG. 3. α-particle pulses near the corona threshold. Experimental conditions as in B. Argon pressure: 50 mm Hg; corona threshold: 765 volts. The upper pulses, taken with a 2000-μsec sweep time, shows the γ_i pulse succession. The first secondary pulse is composed of two distinct peaks due to two different kinds of ions. The lower pulse shows the first part of the upper pulse enlarged. At higher pressure, the separation between the two peaks was not clear.

CONCLUSION

In argon of high purity and with cylindrical electrodes, at pressures above 150 mm Hg, the most important secondary process in the determination of the corona threshold is the photoelectric effect. The γ_p values are of the order of magnitude $1\text{–}5\times10^{-3}$ for brass and nickel cathodes and are not strongly dependent on the conditions of the cathodes surfaces or on the pressures used up to 1000 mm Hg. At pressures between 25 and 150 mm Hg, with the "clean" nickel cathode, the ion-cathode effect plays an important role. γ_i seems to be very dependent on the conditions of the surface. When the surface is not clean enough but is covered by molecular gases, the γ_i is strongly reduced and γ_p remains the only important effect seen at these pressures. It seems interesting to note that in the γ_i process there may be two kinds of argon ions involved, atomic A^+ and molecular A_2^+ ions.[17] The existence of these ions has been discussed extensively elsewhere.[18–20] It is interesting to note that the γ_i pulses shown in Fig. 3 give evidence of the presence of two ions in comparable proportions, at a pressure of 50 mm Hg.

The authors wish to express their gratitude to the Fulbright Committee and the U. S. Office of Naval Research for making possible this clarification of the fundamental mechanisms outlined. They desire to express their thanks to Professor L. B. Loeb for his assistance in this study, for his useful suggestions, and for the hospitality shown in his laboratory. They are furthermore deeply appreciative of the assistance given by all the members of Professor Loeb's Gaseous Electronics group and, in particular, to Mr. Peter Wagner and Miss Elsa Huber for their cooperation. The cooperation of Dr. E. J. Lauer in the interpretation of his work is also much appreciated.

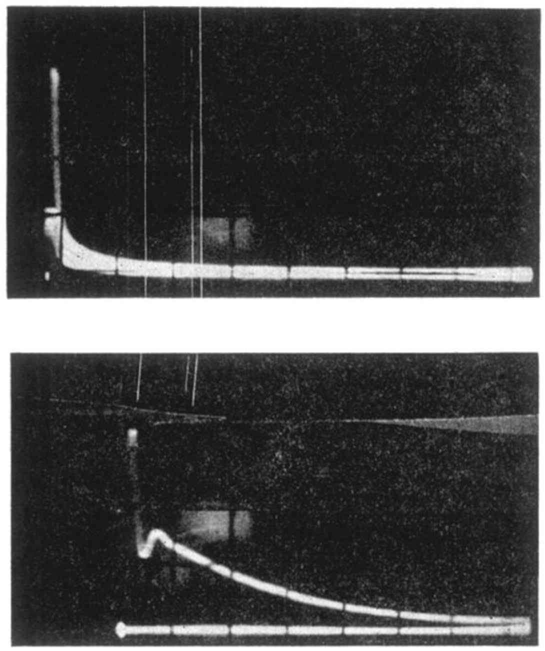
ference, Washington, D. C., October 22–24, 1953, Paper B-9 (unpublished). See also similar effect in J. K. Theobald, J. Appl. Phys. **24**, 123 (1953).

[17] M. A. Biondi in discussion holds that at these pressures only A_2^+ ions exist.

[18] J. A. Hornbeck, Phys. Rev. **84**, 615 (1951).

[19] J. A. Hornbeck and J. P. Molnar, Phys. Rev. **84**, 621 (1951).

[20] A. V. Phelps and S. C. Brown, Phys. Rev. **86**, 102 (1952).



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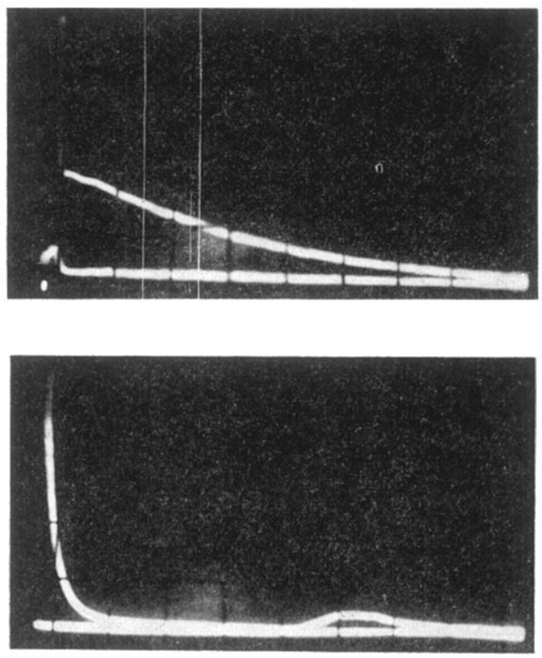

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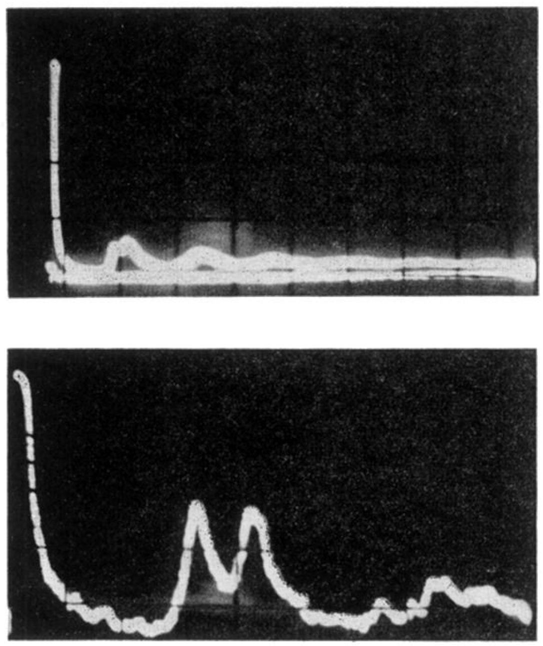

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