ON THE SPECIFIC INDUCTIVE CAPACITY OF METALS.

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IT has long been a question whether the properties of specific inductive capacity and electrical conductivity can co-exist in the same substance. Maxwell's notion that induction is produced by a displacement of the bound electricity in the ether, whether free or between the atoms of a dielectric substance, would make it seem impossible that induction could take place through a body in which electric charges are free to move. Also, since the dielectric constant of a substance was defined as the reciprocal of an elastic modulus, viz., as the ratio of the displacement of an electric charge to the electromotive force which produces the displacement, and since the smallest electromotive force may produce a continuous electric displacement in a conductor, it seems to follow from the definition that the dielectric constant of a conductor is infinite.

However, a closer consideration may show us that this conclusion is not necessary. Thus, one of our modern theories of metallic conductivity assumes that there are in metals both free and bound electrons, and that the free electrons alone are concerned in current conductivity. If this be true, it is not, *a priori*, impossible that an electric displacement in the Maxwellian sense may be produced in these bound electrons by the E.M.F. which produces the current.

It has been found since Maxwell's day that the smallest electromotive force may produce a continuous electric displacement in the free ether; that is, that an electron in the ether outside of material bodies moves with even greater freedom than in a metal, and that electric induction in a vacuum cannot consist in the displacement of the bound electricity in the ether, because there is no bound electricity in the ether. Since we are compelled to look upon induction as something different from a displacement of bound electrical charges, there is no longer any ground for the assumption that a conductor may not possess the property of specific inductive capacity.

Work done in the Stanford laboratory in 1912, by Miss Shirley Hyatt,[1] showed that induction does, in fact, take place freely through a metallic

[1] PHYS. REV., XXXV., 337, 1912.

conductor until the inducing charge is neutralized, so far as its inducing power is concerned, by the bound charge which it induces upon the conductor. Thus, in many inferior conductors a specific inductive capacity may be measured by a rapidly alternating electromotive force when its detection is impossible by a steady electromotive force. In this case, since when the specific inductive capacity is measured by the condenser method the conductivity of the dielectric increases its apparent specific inductive capacity, when an alternating electromotive force is used the more rapid alternations usually give the lower specific inductive capacities.

The work of Alfred Coehn and his colleagues[1] seems to show a very definite relation between specific inductive capacity and contact electrification, so that in the case of all non-metallic substances, solid, liquid or gaseous, substances of higher specific inductive capacities acquire positive charges from contact with substances of lower specific inductive capacities.

Since metallic substances may be charged by contact with other metallic or non-metallic substances, regardless of their conductivity, it would seem that Coehn's Law should apply to them also; and that if metals have the high specific inductive capacities attributed to them they should take positive charges from all other substances.

It is possible to find many lists of substances arranged in the order of their electrification by friction, but in all of these lists, except one[2] which has appeared since the work described in these pages was completed, the metals are usually classed together about midway of the series given, usually between silk and india rubber. This location would seem to make the specific inductive capacity of the metals about four.

However, since the metals may show very considerable contact charges among themselves, it seems unlikely that they should not be distributed throughout the frictional electric series, especially if Coehn's Law may be applied to them. On the other hand, it would seem that if metals take their places distributed throughout the contact series with the non-metallic substances it is natural to conclude that their dielectric constants are also distributed in a similar manner throughout the dielectric series. It was for the purpose of finding if this were the case, and not for determining the contact or frictional series with a high degree of accuracy, that the following described experiments were undertaken. Still, it is believed that for the particular samples of substances used the order is

[1] See A. Coehn, Wied. Ann., 64, 217, 1898; Coehn and Raydt, Ann. d. Phys., 30, 777, 1909; Coehn and Mozer, Ann. d. Phys., 43, 1048, 1914; Coehn and Franken, Ann. d. Phys., 48, 1005, 1915. Also, P. Lenard, Wied. Ann., 46, 584, 1892, and Ann. d. Phys., 47, 463, 1915.

[2] Experiments on Tribo-Electricity, P. E. Shaw, R. S. Proc., Nov. 5, 1917.

undoubtedly correct except in the case of some pairs of metals which lie rather close together in the contact series.[1]

Two methods were employed for testing the charges produced upon the metals by friction or contact. In one of these methods the conducting substances were mounted upon insulating handles, usually of ebonite, and the non-conducting substances were usually held in metallic forceps or tongs to avoid giving them charges by contact with the hand. The two were rubbed together, or merely placed in contact and separated, and their charges were tested by a Wilson tilted electroscope, the plate of which was connected to 100 dry cells. This gave the character of the charges and enabled one to tell whether the substances tested were close together or far apart in the frictional series.

In the other method, the metals to be tested were used in the form of rods. They were suspended from an insulating support and connected to one side of a four-microfarad paper condenser, the other side of which was joined to earth. After the rod had been rubbed or brushed with the substance with which the metal was being compared, the condenser was disconnected from the metal and discharged to earth through a ballistic galvanometer. It was hoped that this second method might give comparable quantitative values, but such was not the case except in a very rough manner. It generally made it possible to determine the order of two metals fairly close together in the series, but even this was not always the case. Since surface conditions, the method of rubbing or brushing the surfaces together and other variations may greatly influence the frictional charges produced, it is very difficult to know that a set of non-metallic substances are arranged in the proper order of their frictional electrification.

In testing the various substances for their places in the series each substance was tried with a considerable number of other substances, usually ten or more, and some substances were tried with practically all the others. In order to make it possible to determine more closely a number of positions in the dielectric series, Professor Rogers kindly determined for me the specific inductive capacity of a considerable number of the dielectrics used. Where his values are used in the table they are followed by the letter R. The other values given were taken from Landolt and Boernstein's tables. The results of the comparison of a number of the substances tried are given in Table I.

[1] Mercury may be made to take its place among the electropositive or the electronegative metals in the contact series. If a solid be immersed in mercury and withdrawn the charges taken by the solid and by the mercury indicate that mercury comes between copper and tin in the contact series; but if any of the solids used in this investigation except the heavy

TABLE I.

Substance.	Sp. Ind. Cap.	Substance.	Sp. Ind. Cap.
Xylenite	—	Ebonite disc	—
Collodion film	—	Beeswax	—
Gun cotton	—	Norway iron	—
Platinum	—	Nickel	—
Sheet rubber A	2.1 R.	Khotinsky cement	—
Brass	—	Quartz, matt face	—
Iron pyrites	—	Aluminium, oxidized	—
Celluloid sheet	—	Silk	—
Gold	—	Lead	—
Silver	—	Bismuth	—
Copper	—	Cadmium	—
Mercury (?)	—	Steel rod	—
Tin	—	Gelatine film	—
Antimony	—	Cobalt glass	4.32 R.
Sheet rubber B	2.34 R.	Quartz, + to axis	4.5
Amber	—	Quartz, = " "	4.8
Sheet rubber C	2.59 R.	Linen	—
Sulphur disc	3. R.	Scratched aluminium	—
Soft rubber tube	—	Flannel	—
Sheet rubber D	3.14 R.	Zinc	—
Copper oxide	—	Boro-silicate crown glass	6.2
Ebonite plate	3.02 R.	Plate glass A	7.6 R.
Paper towel	—	Calcite	8.27
Shellac	3–3.4	Heavy silicate flint glass	8.3
Sheet rubber E	4.2 R.	Chamois leather	—
Yellow oil cloth	—	Heavy flint-glass rod	—

It will be seen from the above table that the metals take their places in the contact or frictional series with dielectric substances just as the latter do with each other. The natural inference to be drawn from this fact is that the places taken by the metals in this series are determined by their dielectric constants, just as are the places of the non-metallic substances. This being true, we may state the following laws:

1. The specific inductive capacities of metals are of the same order of magnitude as are those of non-metallic substances.

2. The more electropositive a metal is in the contact series the higher is its specific inductive capacity.

In a paper published in 1911[1] an attempt was made by the present writer to find the explanation of contact electrification in the different

flint glass rod at the positive end of the series was struck sharply upon the surface of a vessel of mercury it would take a negative charge from the mercury.

[1] A Physical Theory of Electrification, Leland Stanford Junior University Publications, 1911.

specific inductive capacities of the metals, though it was then generally, if not universally, held that the metals have infinite specific inductive capacities. Later, it was shown[1] that for a large number of substances those physical properties which vary with specific inductive capacity vary in the same manner with the magnitude of the characteristic charges taken by ions in electrolytic solutions. Since that time a number of investigations dealing with the problem of the specific inductive capacities of metals have been undertaken in the Stanford Laboratory.

Starting with the theory of Nernst that the high specific inductive capacity of water is the cause of its high dissolving and dissociating power, it was argued in the paper of 1911 that if two pieces of the same metal be placed in communicating liquids of different specific inductive capacities the one in the liquid of higher specific inductive capacity will give off positive ions more freely than the one in the liquid of lower specific inductive capacity, and hence will become the cathode of a voltaic cell whenever the two pieces are metallically connected. This has since been verified for a number of dielectric liquids of known specific inductive capacity by Mr. Dayton Ulrey,[2] who found that the electromotive force of a cell having both electrodes of the same metal is directly proportional to the difference in specific inductive capacities of the two liquids in which the electrodes are immersed.

Previous to the work of Ulrey, Miss Finney[3] had shown that for a large number of pairs of equimolecular solutions of metallic salts with a common acid, "the metals may be arranged in a series in the order in which the presence of their ions in a water solution affects the solution tension of a metal when placed in the solution. Furthermore, this series is the same as the contact electromotive series. That is, if both electrodes be of the same metal, the electrode in the solution which contains the more electropositive ion has the higher solution tension and accordingly corresponds to the zinc electrode, while the electrode in the solution which contains the less electropositive ion corresponds to the copper of the ordinary Daniell cell."

The conclusions of Miss Finney were confirmed by the later work of Mr. Philo F. Hammond,[4] who measured by another method the potential difference between electrodes of the same metal in equimolecular solutions containing different metallic ions with the same acid ion.

[1] Specific Inductive Capacity and Atomic Charges, PHYS. REV., N. S., I., 446, 1913.

[2] Results of investigation not yet published.

[3] PHYS. REV., N. S., VI., 400, 1915.

[4] The Influence of the Metallic Ions in an Electrolytic Solution Upon the Electrical Potential of a Metal Placed in the Solution. The New Era Printing Company, May, 1916,

The necessary interpretation of the above results seems to be that metallic ions in a water solution usually decrease the specific inductive capacity of the water, but that the more electropositive ions decrease the specific inductive capacity less than the more electronegative ions, all of which is in agreement with the above deductions as to the magnitude of the dielectric constants of metals.

STANFORD UNIVERSITY,
February, 1918.