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XX. On the permanent electret

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XX. *On the Permanent Electret.* *By* Mototarô Eguchi, *Professor of Physics, Higher Naval College, Tokyo, Japan* *.

Introduction.

"ELECTRET" is the name given to the dielectric which is electrized † permanently by a special treatment due to the author. Some waxes and resinous materials have moderate conductivity in their liquid state, while they are very good insulators in the solid state. The electrical conductivity of these materials varies gradually with the degree of solidification, and when the materials get moderately hard the conductivity becomes practically nil. The author let solidify a mixture of these materials in a strong electric field applied through all the time in which the solidification went on. The dielectric taken out of the field, after having been cooled sufficiently, showed very strong polarities on its two surfaces which were kept in contact with the electrode plates during the preparation. The electrization of such a dielectric could not be destroyed by several treatments, such as touching by Bunsen flame, exposure to X-rays, planing with knife, washing with some solvents, &c. Nor did it die away after the lapse of many years. From several subsequent studies, it has become evident that the electrical change of the dielectric is not of a superficial nature, but that it is a permanent internal change within the material.

The name "Permanent Electret" or simply "Electret" was given to the special dielectric at the ordinary meeting of the Physico-Mathematical Society of Japan, February 21, 1920 ‡. Later, I found in Oliver Heaviside's 'Electrical Papers' the section with the title "Electrization and Electrification. Natural Electret" §. In this paper he proposed for the first time to use the term "Electret" to fill the want for describing an intrinsically electrized body, and some possibilities of electrets were discussed on the theoretical points of view. The present method of preparation was,

* Communicated by the Author.

† The term "Electrization" is used after Heaviside to signify the internal electrical change of a material, which is different from superficial electrification.

‡ Mototarô Eguchi, Phys.-Math. Soc. Japan, ser. 3, vol. ii. no. 7 (1920).

§ Oliver Heaviside, 'Electrical Papers,' vol. i. § xii.

however, obtained independently and also in a way utterly different from his discussions.

The electret shows so great an intensity of electrization that the electric force exerted in front of the surface of the electret may attain the greatest sustainable value in the atmosphere. The permanency is also so good that we have detected no sensible decaying for these three or more years since the preparation.

§ 1. *Preparation of the Permanently Electrized Dielectric.*

From the study of the variation of conductivity with the solidification of waxes and some other materials *, I came to think it possible to get a permanently electrified or more correctly electrized dielectric by allowing some kind of waxes to solidify in a strong electric field.

After many trials, it has been ascertained that the disk-shaped electret of a certain size is one of the most convenient forms for several reasons, except for the cases in which special studies are wanted. The method of preparation of the disk-electret is, therefore, briefly described here.

A shallow circular metal basin B (fig. 1), depth 1 cm., diameter 20 cm., is put on a pole-plate P_1, a little larger in diameter than the basin. The plate itself is placed on three sulphur insulators S_1, S_2, S_3, which are laid on a wooden tripod stand T capable of levelling by the three screws f_1, f_2, f_3.

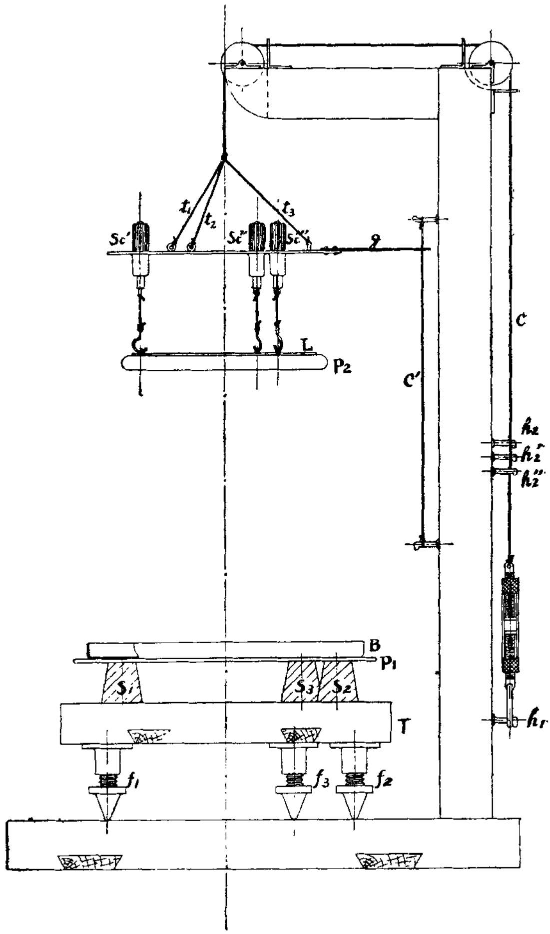
As the other electrode, a hollow metal disk P_2 is suspended by three insulating cords, t_1, t_2, t_3. These cords are made of Japanese fishing-lines, Tegusu (a kind of thick silk thread), whose surfaces have been treated with a mixture of some waxes and resin to get rid of the surface leakage. The basin and the disk-electrode are coated with tin-foils (not shown in the figure). The lead sheet L is used as a weight to cause the foil tightly to attach itself to the disk.

As the preparatory adjustment, the levelling of the basin B is first effected by three screws f_1, f_2, f_3; secondly, the hook at the end of the cord C is transferred from the arrester h_1 to another h_2, and the plate P_2 is so regulated by three screws Sc$'$, Sc$''$, Sc$'''$ that its lower surface comes

* Mototarô Eguchi, Phys.-Math. Soc. Japan, ser. 3, vol. i. nos. 10–11 (1919).

just up to the margin of B. Another cord C′ stretched through a hole perforated near the end of the guider *g* serves to prevent the oscillation of the electrode P_2.

Fig. 1.



After raising the disk-electrode P_2 up to a sufficient height, the material melted at a temperature far above its melting-point (about 130° C.) is poured in to fill up the basin B, and then P_2 is put on the melted dielectric so that it rests just on the surface of the dielectric. The air bubbles, if any, on the surface of the melted material may be easily taken off by touching with a small Bunsen flame.

Care was taken to adjust the voltage of the high tension source in order to prevent any undesirable effect such as brush discharges between the electrodes along the surface of the dielectric when it solidified partially. Tin-foils were applied on the electrodes, so that not only did the dielectric not adhere directly to the metal surface, but it might also contract freely as it cooled, and when the dielectric solidified completely the disk-shaped material might be easily taken off from the basin. Moreover, with the disk-electret thus obtained, both surfaces upper (U) and lower (L) might be studied at will.

§ 2. *The Charge of Temporary Nature and the Permanent Electrization of the Electret.*

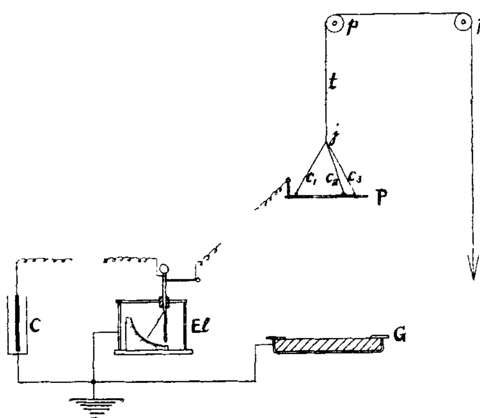
As the material for the permanent electret, a mixture consisting of equal parts of carnaüba-wax and resin with or without a certain amount of bees'-wax was found to be very good as regards the intensity of electrization and the permanency. If we prepare a disk-electret of this material, joining for instance the upper surface (U) to the positive pole of the high tension source, and the lower surface (L) to the negative, we first detect in general a surface charge of negative sign on the upper surface, and one of positive sign on the lower, soon after we take the electret out of the preparing arrangement. But these kinds of charges are of temporary nature, and they die away gradually, in a comparatively short time (in one or two days). After the complete decay of such charges, the surface charges of opposite signs respectively to the above gradually grow up. The positive charge on the upper surface and the negative on the lower, which are respectively of the same signs as those of the applied poles of the source during the preparation, tend to grow to their ultimate values in a few days. The manner of growth of these charges on both surfaces and their values do not vary much even when the method of preparation is modified in some way: for example, when both electrodes are completely insulated from the earth, or when either one of the electrodes is completely earthed and the other insulated. The permanency of these charges is so good that we cannot detect any sensible decay after many years, as will be shown later on (see § 8). We shall call these surface charges of the electret the free charges due to its proper electrization.

§ 3. *On the Method of Measuring the Surface Density of the Free Charge.*

Before entering upon the details of the behaviour of the electret, it will be convenient to describe the method of measuring the surface density of the free charge which was found to be the most simple and reliable.

The arrangement is shown in fig. 2. P is an induction plate of a circular form, diameter 12 cm., with a guard-ring G. The induction plate may be kept at any desired height by means of three insulating suspension cords c_1, c_2, c_3, and a thread t attached to the common joint j of these cords, passing over pulleys p and p'. The size of the plate was

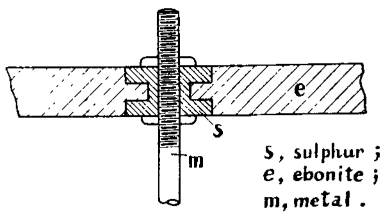
Fig. 2.



chosen so large that the electrization of the portion of the dielectric under the plate was quite uniform, and the guard-ring G with a small air-gap was employed for eliminating the end effect on the induction plate. To the induction plate, a calibrated electrometer El and a variable condenser C are connected by means of soft springs of thin wires. Putting the disk-electret together with its metal basin in the proper position under the induction plate, the earthed guard-ring is first laid on the surface to be measured. The induction plate is then put in its position on the surface, the system being always kept earthed during this process. Disconnecting the earth line of the plate system, and lifting the plate to such a height that the influence of the dielectric on the plate was no longer sensible, the electrometer reading was taken. As to the insulation of the condenser, special care was taken to get rid of the surface leakage. The metal rods of the condenser plates were suspended through the central holes of the sulphur pieces moulded in the form shown in fig. 3.

Such a moulded piece of sulphur has a sufficient mechanical strength, and it was ascertained that the condenser might be used in any wet atmosphere without fear of any appreciable leakage.

Fig. 3.



The surface density σ of the free charge of the electret may be calculated from the observed numbers as follows :—

$$\sigma = \frac{C \cdot V}{\pi r^2},$$

where C is the capacity of the condenser system, V the potential read by the electrometer, r the effective radius of the circular surface of the induction plate (radius of the plate + one-half of the air-gap). Any conducting agent, such as moisture, dust, free ions, &c., if present on the dielectric surface, may reduce the electrostatic induction on the plate. It is very difficult to keep the surface quite free from such disturbances. Moreover, the irregularity of the surface of the electret may have an influence on the induction of the plate. The value of σ estimated as above may, therefore, be somewhat smaller than the true value.

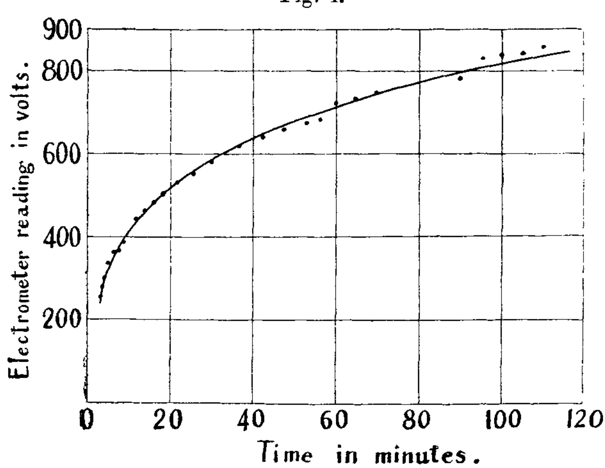
The sign of the induced charge was determined every time and that opposite to this sign was taken as that of the free charge.

§ 4. *Action of X-rays on the Electret.*

If the surfaces of a disk-shaped electret are exposed to X-rays for some time, the free charges on the surfaces apparently disappear. The surface density of the free charge reappears, however, gradually, and attains its final proper value estimated before the exposure. However many times the exposures are repeated, the recoveries are always complete. By the time of exposure, the nature of the X-rays and the intensity of the rays, the rate of recovery is influenced in greater or less degree. But in any case, when the free charge has recovered itself completely, the final surface density is always the same, and shows a definite value proper to the electret.

Several methods of exposing the disk-electret to X-rays were tried. In one case, the X-rays were sent in the direction normal to the disk-surface, allowing the rays to pass through the dielectric material. In another case, the X-rays were let go along the disk-surface, the edge of the disk being protected from the rays by a lead band of a sufficient breadth, and thus the rays were cut off and could not go through the dielectric material. In either case, we did not find any material difference in the temporary disappearance of the free charges and their spontaneous recoveries.

Fig. 4.



This temporary disappearance of the free charge and its recovery afterwards might be explained on the view that the ions in air produced by X-rays are caught on to the surface by the charges of opposite sign respectively, and when the action of the X-rays ceases, the ions fly off spontaneously from the surface by their kinetic energy of agitation, opposing the electrostatic attraction of the free charges of the dielectric surfaces on the ions. A few examples of the observed facts are given below.

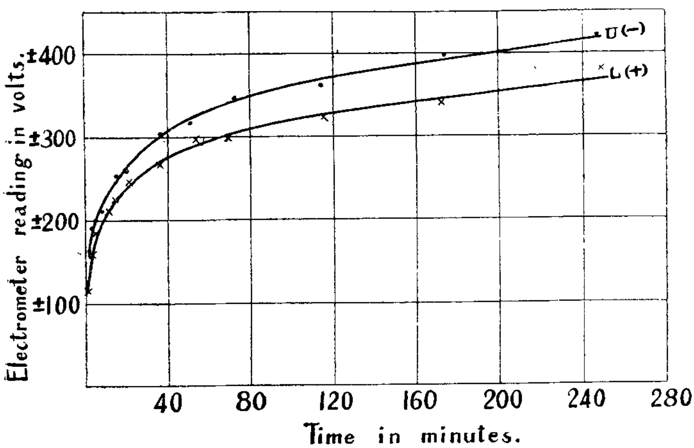
In fig. 4 the time curve of the recovery of the free charge after an exposure to very soft X-rays is plotted, the surface of the disk-electret being kept bare during the recovery. The recovery obeyed very nearly an exponential law,

$$V' - V = (V' - V_0)e^{-\lambda t},$$

where V is the potential of the electrometer at time t, and V' the final potential which corresponds to the ultimate free charge.

In fig. 5 the simultaneous recoveries of the charges of both surfaces, upper and lower, of one disk-electret are given.

Fig. 5.



The small difference of the ultimate values of the surface densities for the two surfaces will probably be due to the difference of the condition of the two surfaces, such as the non-uniformity of the electrization near the rim of the surface, &c.

§ 5. *Evidences for Permanent Internal Electrization in the Dielectric.*

Many experimental studies were carried out for testing the author's view that the electrification measurable as the surface density of opposite signs appearing respectively on the two surfaces of the special electret are the free charges of the permanent electrization within the material. The brief description of the results of these studies will be given below.

(1) Temporary disappearance of the free charges by X-ray exposure and their complete recovery after the withdrawal of the rays (as stated in the preceding section).

(2) The behaviour of the free charges after the treatment of the surface by a Bunsen flame is very similar to the effect of X-ray exposure.

When the surface of the electrized dielectric was treated with a Bunsen flame in such a degree that some surface layer of the dielectric material was melted and again solidified after the withdrawal of the flame, the surface charge was very much reduced, or sometimes it completely vanished, if measured soon after the treatment. This disappearance was, however, only temporary, and the free charge recovered itself, as was seen in the case after an X-ray exposure.

(3) Effect of planing with knife.

I planed with a sharp knife both upper and lower surfaces of an electrized dielectric to some depth, so that the old surfaces no longer remained. The free charges were apparently reduced to a small amount, but they recovered gradually as they did after the exposure to X-rays, the only difference from the latter case being that the recovery was somewhat irregular. When the free charges had recovered completely, I tried the knife treatment once more to the depth of some mms., after which the recovery was also similar and perfect, and the ultimate values of the free charges were very near to those before the treatment.

(4) Effect of washing with some reagents.

I studied the effects of washing the electret surfaces with some reagents such as water, acids, alkalis, absolute alcohol, ether, benzene, &c. Though the free charges disappeared after such a treatment, they always recovered some time after the dielectrics were made completely dry. The results were, thus, also affirmative for the permanent internal electrization of the material.

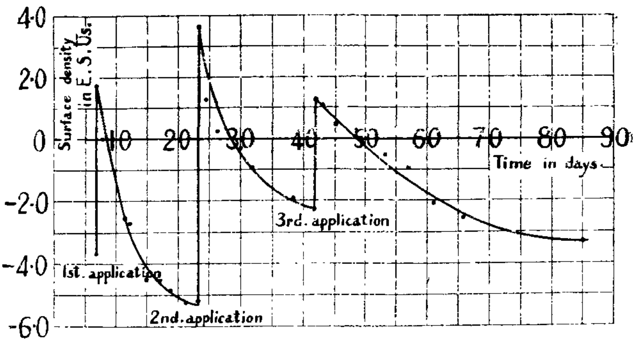
(5) Comparison of two pieces of dielectrics of the same materials, one of which was electrized by the special treatment, the other merely superficially charged by means of an ordinary process.

The dielectric material was solidified in a metal basin under conditions otherwise the same as in the preparation of the special electret in every respect, but applying no electric field. After the solidification was completed, the material was put under the action of an electric field for a sufficiently long time of one hour or more. Such a dielectric, soon after the treatment, takes strong surface charges of opposite polarities on its surfaces. Though these surface charges displayed some weak residual charges, their intensity and durability were of very small order quite incomparable with those of the electret.

(6) Effect of electric force on the electret.

Different electric forces were applied on some disk-electrets, and the effect of such forces on the electrization of the material was observed. I took two of them of which the sense of electrization was known. For convenience' sake, the electric force in the same sense as the field employed in the preparation for an electret will be called "positive," and that of the opposite sense "negative." To the first disk A_3 a negative electric force was applied for thirty minutes, and afterwards the variation of the free charges was observed. The results of the observation repeated three times successively are plotted in fig. 6, the surface density of the

Fig. 6.

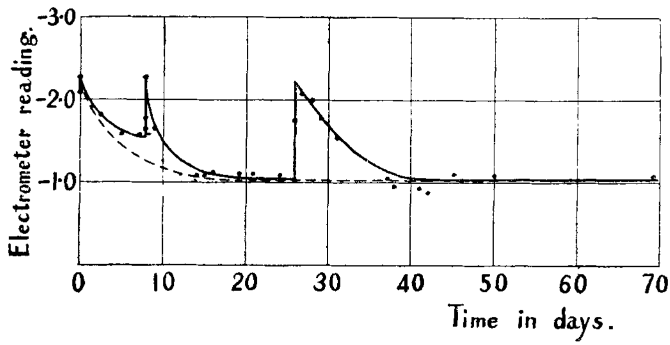


upper surface U only being shown in the figure, since the other surface L showed a behaviour similar to U in every respect but with the sign of its charge opposite.

As we see on the figure, seven days after the preparation, the disk had a free charge of negative sign on surface U and of positive on L, nearly settled at their full values. By the application of the negative electric force for thirty minutes, the surfaces got moderately large surface densities of the signs respectively opposite to those of the free charges of the proper electrization. These temporary charges, however, decayed rapidly, and the gradual growth of the surface charges due to the original electrization followed. When the rate of growth of the surface charge became very small, the second and the third applications of the negative electric forces were tried successively, and the results were always of the same nature as in the first application.

With the second disk W_2, the effect of applying the positive electric force was studied. Though small temporary increases of the surface charges were observed after the application of this force, they settled rapidly to their proper value due to the electrization. The results are depicted in fig. 7.

Fig. 7.



From these experiments we may safely conclude that, by the application of an electric force, positive or negative, on a prepared electret, the surface electrification may be disturbed in some degree, but the permanent electrization of the electret remains almost unaffected.

§ 6. *On the Intensity of Electrization of the Permanent Electret.*

From many experimental studies made by the author * the internal electrical change of the permanent electret was concluded to be of the nature of "polarization," *i. e.* every portion from element to element of the dielectric material was in a state of having acquired equal and opposite electrical polarities on its two ends.

The surface density of the free charge measured by means of the method described in § 4 may, therefore, be taken as the intensity of permanent electrization within the dielectric. Most electrets of which the materials consist of carnaüba-wax and resin with or without some percentage of bees'-wax, have so great intensities of electrization that they exceed the greatest possible surface densities of the electrifications charged on some good insulators such as sealing-wax, shellac, sulphur, &c., by means of mechanical friction. The following numbers are given to show the comparison of these surface densities.

* Mototarô Eguchi, Phys.-Math. Soc. Japan, ser. 3, vol. v. no. 8 (1923).

TABLE I.

Maximum attainable surface densities by mechanical friction *.

Material.	Rubbed on wool. Max. surf. density.	Rubbed on silk. Max. surf. density.
Sealing-wax	5·70 E.S.U.	5·40 E.S.U.
Shellac	5·57 ,,	5·12 ,,
Sulphur	5·48 ,,	5·39 ,,
Ebonite	4·82 ,,	4·43 ,,
Amber	4·18 ,,	4·11 ,,
Glass	2·65 ,,	2·90 ,,

TABLE II.

Surface densities of the free charges of the internal electrization of the permanent electrets.

Disk-electret O_1, prepared Oct. 27, 1919.

Date (*d*).	Time since the preparation (*t*).	Surf. (*s*).	Surf. density (σ).	Electric intensity in air in front of the surf. (E).
Mar. 22, 1921...	$1^{y.}\ 5^{mon.}$	U	−5·7 E.S.U.	−72 E.S.U.
		L	+6·2 ,,	+78 ,,
Mar. 3, 1922...	$2^{y.}\ 5^{mon.}$	U	−6·5 ,,	−82 ,,
		L	+6·2 ,,	+78 ,,

Disk-electret R_1, prepared Oct. 30, 1919.

d.	*t*.	*s*.	σ.	E.
Mar. 22, 1921...	$1^{y.}\ 5^{mon.}$	U	−5·6 E.S.U.	−70 E.S.U.
		L	+5·6 ,,	+70 ,,
Mar. 3, 1922...	$2^{y.}\ 5^{mon.}$	U	−6·0 ,,	−75 ,,
		L	+5·8 ,,	+73 ,,

The electric intensities in air in front of the surfaces of the electret are calculated from $E=4\pi\sigma$, and are given in the last column in the above table. Lord Kelvin found that the electric intensity sustainable in air was 130 E.S.U., and therefore the corresponding surface density was 10 E.S.U. These numbers might, however, hardly be realized in a very good condition of air. The numbers of the permanent electrets are not much smaller than these limiting values. It will be observed, in what a higher order of intensity of electrization the electrets are than the ordinary residual electricities in dielectrics hitherto known.

* L. Graetz, *Handbuch der Elektrizität und des Magnetismus*, Bd. i. Saite 10 (1918).

§ 7. *On the Permanency.*

The disk-shaped electrets are kept usually with their surfaces covered with earthed tin-foils. Under this surface condition, the surface density of the free charge of the electrization remains nearly constant for many years, though small fluctuations may occur probably due to the atmospheric conditions such as the temperature and humidity. Some disk-electrets were tested by keeping them in this condition during three years or more since their preparation, their surface densities being measured at moderate intervals. No natural decay of the surface densities was observed. In the following table two examples of the records of the electrets kept in such a condition are given.

Table III.

Surface density of the free charge of the electrization.

Disk-electret O_1.

Date	Oct. 27, 1919.	Dec. 23, 1920.	Dec. 24, 1921.	Mar. 3, 1922.	Dec. 20, 1922.
Surf. density in E.S.U. or other remarks.	prepared	U −4·5 L +5·6	U −5·8 L +5·1	U −6·5 L +6·2	U −5·1 L +7·2

Disk-electret R_1.

Date	Oct. 27, 1919.	Dec. 23, 1920.	Dec. 24, 1921.	Mar. 3, 1922.	Dec. 20, 1922.
Surf. density in E.S.U. or other remarks.	prepared	U −5·1 L +5·6	U −5·8 L +4·7	U −6·0 L +5·8	U −6·2 L +7·2

If the electret is kept with its surfaces bare, the surface density apparently decays in some degree. The final reduced value of the surface density seems, however, to be kept at some amount different from zero. It is worth noticing that, for observing these decays definitely, it is necessary to keep the electret on some pointed supports in a dry and dust-free air in a desiccator. Otherwise a coating of dust attracted by the free charge behaves as an earthed conductor.

If an electret, whose free charge has thus decayed to a small amount, is again kept covered with tin-foils applied on both surfaces the free charge recovers itself gradually, and at last its surface density attains its proper value. The length of time during which the surfaces are kept bare may affect somewhat the rate of recovery of the surface density when the electret is again covered. The final surface density seems, however, to take the definite value proper to the electret.

The disk-electret M_2 was taken for this kind of tests, and the results are given in Table IV.

TABLE IV.

Disk-electret M_2.

Date...	Nov. 30, 1920.	Dec. 10, 1920.	Dec. 15, 1920.	Dec. 18, 1920.	Oct. 18, 1921.
Surf. density in E.S.U. or other remarks.	prepared	U −5·1 L +6·7	U −4·2 L +5·8	U −2·5 L +2·5	U −0·1 L +0·05
Surf. condition.		← kept covered with tin-foils. →		← kept bare in ordinary atmosphere; both surfaces were coated with dust. →	← both surfaces cleaned with feather brush and then exposed to X-rays.

Date	Oct. 22, 1921.	Nov. 12, 1921.	Jan. 14, 1922.	Jan. 30, 1922.	Mar. 6, 1922.
Surf. density	U −0·2 L +0·1	U −3·5 L +3·1	U −0·1 L +0·08	U −2·5 L +1·9	U −4·2 L +3·2
Surf. condition		kept in a desiccator with both surfaces covered. →	← kept in a desiccator with surfaces bare. →	← kept in a desiccator with surfaces covered. →	surf. density moderately great; permanency good.

Summary.

1. The Permanent Electret was made of a certain mixture of wax and resin, keeping it in a strong electric field during its solidification.

2. The nature of the electrical change of the dielectric is a permanent internal electrization of the material entirely different from the superficial electrification.

3. The electrization cannot be destroyed by different treatments applied on the surface such as Bunsen-flame treatment, X-ray exposure, washing with some solvents, planing with knife, applying electric force in any sense, &c.

4. The intensity of electrization of the electret attains such a high degree that the electric intensity in air in front of the electrized dielectric takes nearly the greatest sustainable value.

5. The permanency of the electrization is also extremely

good, so that we have detected no decaying for three years or more since the preparation.

In conclusion, the author wishes to express his best thanks to Dr. Terada, Prof. of Tokyo Imperial University, and Dr. Honda, Prof. of Tohoku Imperial University, for their continued interest in the present investigation.

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XXI. *Abnormal Reflexion of X-Rays.* By J. H. Smith, *M.Sc., Assistant Lecturer in Physics, University College, London* *.

CLARKE and DUANE† have found, by the ionization spectrometer method of Bragg, certain diffraction maxima which do not obey the two laws governing the Bragg maxima, namely—the angle of incidence equals the angle of reflexion, and that the orders of spectra are given by

$$n\lambda = 2d \sin \theta,$$

where λ is the wave-length of the rays and d the distance between planes concerned.

Prior to this Duane ‡ had discovered maxima obeying the Bragg laws, but due to characteristic radiation produced by fluorescence of atoms in the crystal.

If this set of maxima exists it is easily shown that an "abnormal" set must also exist; and also that this second set will be of greater intensity than the first set. This abnormal set also exists when there is no fluorescence.

These abnormal maxima are due to the periodicity of scattering centres in the planes themselves, and, unlike the main Bragg maxima, the positions of the abnormal sets will vary as the crystal is rotated about the normals to the planes producing them.

Consider a plane wave of homogeneous radiation incident on a set of planes a distance d_2 apart, at a glancing angle θ. Bragg § considers each plane as continuous, and this is sufficient for the set of maxima which is primarily related to d_2. For the general maximum the planes of spacing d_2 can be considered as made up of scattering centres with a spacing d_1 in the plane of incidence.

* Communicated by the Author.
† Proc. Nat. Acad. Sci. ix. 4. p. 131 (1923).
‡ Proc. Nat. Acad. Sci. viii. 5. p. 90 (1922).
§ 'X Rays and Crystal Structure,' 2nd edition, p. 12.