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W.C. Röntgen

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XXVIII. *On the Thermoelectric, Actinoelectric, and Piezoelectric Properties of Quartz.* By W. C. RÖNTGEN*.

THE last of the experiments described in my second communication on the optical behaviour of quartz in the electrical field induced me (as already mentioned†) to investigate experimentally the electrical properties of quartz, especially its thermoelectric and actinoelectric properties. In this investigation I very soon arrived at the conclusion that it is possible to refer to a common cause the evolution of electricity brought about in very different ways, whether by conduction of heat, radiation, or alteration of pressure—namely, to a change in the strains produced in the crystal by any means. I therefore consider it unnecessary to distinguish the three kinds of electricity named as differing from each other in their mode of production, and should propose to retain only the name piezoelectricity, if further investigation should show that the method of explanation indicated is applicable in all cases and sufficient. I have delayed the publication of this view and of these experiments, in the first place because the experiments were not altogether complete, and, secondly, because my theory is so entirely at variance with that proposed by so experienced and skilful an experimenter as Herr Hankel. It seems to me now, however, not possible to wait longer; and in the following I briefly describe the most important of my experiments.

I think we may conclude, from the electro-optical experiments described, that increase of a uniform surface-pressure exerted all over a quartz cylinder or quartz sphere produces such an evolution of electricity that the surface is divided by the three planes of no piezoelectricity into six electrical fields, which have the same position and sign as those obtained by the method of increase of pressure in one direction, described on p. 100 of my second paper (Phil. Mag. August 1883).

If we bring a non-electrified and hot sphere, having a uniform temperature all over, into a colder space (so that it can cool uniformly), the external layers, which cool first, will exert a pressure upon the inner ones everywhere in a radial direction, which will increase rapidly at first: consequently during this period, which we will call the first, we shall have the same distribution of electricity upon the sphere which corresponds to an increase of surface-pressure mechanically exerted upon it. After some time, when the cooling has

* Translated from a separate impression from the *Ber. der Oberh. Ges. für Natur- und Heilkunde*, communicated by the Author.

† Phil. Mag. August 1883, p. 109.

advanced further, the pressure exerted by the outer layers does not increase any more, but begins to diminish; but then the sign of the piezoelectricity evolved changes also, and the electricity produced during the first period becomes more and more weakened. During this second period the sphere becomes continually less strongly electric; and it may happen, especially if a part of the electricity produced has disappeared by conduction during the first period, that the all but cold sphere shows an electrification which is the opposite of that found when the cooling commenced.

These conclusions I have been able to verify repeatedly by observing the electricity appearing upon a sphere of quartz freely suspended, during cooling. Herr Hankel* has also observed the phenomena just described with quartz crystals. He, however, calls the electricity which makes its appearance at first actinoelectricity, and that remaining at the last thermoelectricity.

By heating a quartz sphere as uniformly as possible, I have obtained phenomena altogether analogous to the preceding; but the electricities are now of the opposite sign.

If we observe that the outer layers which receive the heat first exert upon the inner ones a radially directed tension, and that, by increase of a tension exerted upon the quartz, the same piezoelectricity is produced as by the decrease of pressure acting in the same direction, the explanation becomes easy.

Local cooling of a previously heated crystal by means of a cold stream of air directed against the crystal produces an energetic evolution of electricity at the points cooled, if these points did not lie exactly in a plane of no piezoelectricity; the nature of the resulting electricity was the same as that which would be produced at the same place by the increase of a pressure exerted there in the direction of a diameter. Local heating by a current of warm air produced, on the other hand, electricity of the opposite kind. In the first case we have a rapid increase of the pressure exerted by the outer layers upon the inner ones; in the second case, where the outer layers tend to raise themselves above the inner ones, the resulting tension increases very rapidly. I therefore consider the electricity produced to be simply piezoelectric. The electricity which Herr Friedel observed to be produced by placing a heated metal ball upon a quartz crystal is identical, both in sign and in mode of production, with that produced by a hot current of air: it is therefore piezoelectricity. Herr Friedel calls it thermoelectricity; Herr Hankel actinoelectricity.

* Hankel, 'Electrical Researches,' Abhandlung 15, p. 530.

The following experiments seem to me peculiarly adapted to support my theory.

A ring of tinfoil, of internal diameter 2 centim. and exterior diameter 4 centim., was cemented to a homogeneous plate of quartz cut at right angles to the principal axis; the ring was then cut through radially at six points in the direction of the axis of no piezoelectricity, so that six pieces of the ring, insulated from each other, were obtained. The first, third, and fifth pieces were connected by wires with one half-ring of a Kirchhoff-Thomson electrometer, the second, fourth, and sixth pieces and the other half-ring of the electrometer being connected with the earth.

If then, the plate possessing, to begin with, the temperature of the room, the central uncovered portion was heated by placing a warm metallic cylinder upon it, or by radiation from a flame or from a heated piece of metal, or by a current of hot air, or in any other way, then the portions of the ring became electrified, so that each portion of the ring acquired the same electricity as the end of the secondary axis lying next it would have acquired if there had been increase in a pressure acting in the direction of the corresponding secondary axis. Cooling of the central portion produced in any way, on the other hand, always produced the opposite electricities.

If now, in a subsequent experiment, it was not the central portion of the plate, but that surrounding the tinfoil ring which was heated or cooled as the case might be, then, in case of heating, the electrometer showed the presence of the same electricity previously found by cooling the centre, and conversely, in case of cooling, the same electricity as was produced by heating the centre.

These results are not surprising if we start from the view that changes in tension in the crystal are the cause to which the evolution of electricity is due. In the first and fourth cases, for example, heating at the centre, or cooling at the periphery, produces tensions in the plate which are of the same kind as those produced by a uniformly distributed pressure exerted upon the edge. In the second and third cases central cooling or peripheral heating produces a condition of tension analogous to the condition brought about by a uniformly distributed tension exerted upon the edge. In all cases, during the time immediately following the heating or cooling as the case may be, a rapid increase of the tensions produced takes place. Consequently in the two cases first mentioned there must be the same distribution of electricity as would correspond to an increase of the pressure exerted upon

the edge of the plate; in the two last-mentioned cases, the distribution corresponding to a diminution of pressure.

We see from these experiments that the nature of the electricity produced is not dependent upon the particular method by which a local heating or warming is produced, but depends essentially upon the position in the crystal of the point where these changes in temperature take place. From the result that heating the peripheral portions of the plate and heating the central portions produce opposite electrical effects, I am disposed to draw a conclusion, which indeed has not yet been experimentally demonstrated but which seems to me tolerably safe. If we suppose it possible to warm a plate so uniformly that no perceptible differences of temperature or tensions should be produced, then I believe that this heating would produce no electricity or relatively very little, although the particles of the plate suffer considerable displacement amongst themselves. If, now, we consider that even very small displacements of the particles produce very considerable quantities of electricity, if these displacements are accompanied by changes of tension in the crystal (as is the case, for example, with irregular heating of a plate), the assumption seems to be justified that change of temperature and position of the particles in itself produces no electricity, but that, on the other hand, the real cause of the evolution of electricity is to be found in changes of tension.

In what has been described I have made a first attempt to explain the electricity produced in quartz by change of temperature as due to stress produced in the crystal. I am well aware that the explanation given in the separate cases is here and there defective, and that further investigations are necessary in order to establish the exact connexion between changes of temperature and evolution of electricity.

Giessen, March 20, 1883.

XXIX. *On Concave Gratings for Optical Purposes.* By
HENRY A. ROWLAND, *Professor of Physics, Johns Hopkins
University, Baltimore**.

General Theory.

HAVING recently completed a very successful machine for ruling gratings, my attention was naturally called to the effect of irregularity in the form and position of the

* An abstract of this Paper with some other matter was given at the Physical Society of London in November last, the Paper being in my hand in its present shape at that time. As I wished to make some addi-