BECQUEREL RAYS, A RESUME.

BY OSCAR M. STEWART.

THE importance of the subject of Becquerel rays has increased almost beyond expectation during the past year or two. Not content with attributing to Becquerel rays all the properties of X-rays, physicists and chemists have found that these rays also possess properties hitherto attributed to kathode rays alone. In its changed aspect it is believed that work along this line will throw light not only on the subjects of kathode rays and X-rays, but possibly on the constitution of matter itself. It has therefore been thought advisable to bring up to date the résumé given over two years ago in this JOURNAL.¹

In his earlier work Becquerel thought that he had proven beyond all doubt that the radiations from uranium could be reflected, refracted and polarized. It was upon these experiments that the ultraviolet light theory of Becquerel rays was based. No one, including Becquerel himself, has been able to repeat these decisive experiments, and Becquerel now admits that he was mistaken and probably deceived by the presence of a "secondary" radiation. With this exception all the early work on uranium radiations has been confirmed.

Uranium no longer stands as the only element known to emit of its own accord a persistent radiation, and the name Becquerel rays is now applied to the radiations from a number of substances. Some of these radio-active substances have been found to be elements which were hitherto unknown.

Mme. Sklodowska-Curie² in searching for other elements or substances which gave radiations similar to those emitted from uranium, found that the oxide of thorium appeared to emit a radiation even more intense than that from uranium. Electrified bodies were more quickly discharged when brought near thorium oxide than when near uranium. G. C. Schmidt³ independently discovered the radiant activity of thorium and also found that both the element and its compounds imparted conductivity to gases and affected photographic plates. He failed to find any evidences of polarization but thought that he obtained refraction by glass. Mme. Curie had noticed⁴ that pitch blende or uraninite and chal-

¹ PHYSICAL REVIEW, VI., p. 239, April, 1898.

² Comptes Rendus, 126, p. 1101.

³ Wied. Ann. 65, p. 141, 1898.

⁴ C. R., 126, p. 1101.

colite (phosphate of copper and uranium) were more active than should be expected from the amount of uranium they contained. In fact they were even more radio-active than uranium itself. This led her to suspect that they contained some material more active than uranium. This seemed more probable when she found that the radiation from natural chalcocite was more intense than that from artificial chalcocite, although they contained the same amount of uranium. After chemical analysis M. and Mme. Curie found that the bismuth compounds obtained from pitch blende were very active. They concluded after examining a large number of elements and substances that they had found as an impurity in the bismuth salts a new element. This element, after Mme. Curie's native country, they called *polonium*. When tested by Demarçay no characteristic lines were observed in its spectrum. But this is also true of uranium, thorium and tantalum, which give innumerable fine lines difficult to recognize. At first only a trace of polonium was found in the bismuth salts. Even this gave a radiation several hundred times as intense as that from uranium. As polonium behaves analytically almost like bismuth, they did not succeed in entirely isolating it from bismuth. The partial separation obtained was by utilizing a difference in solubility and volatilization. For Mme. Curie's researches in magnetism and the discovery of polonium and the radiant activity of thorium the French Academy of Sciences awarded her the *Prix Gœtze* of 4000 francs.

Continuing this work on the pitch blende derivatives, M. and Mme. Curie and G. Bémont¹ found that the barium salts obtained from pitch blende contained in small traces another element analytically behaving as barium, but extremely active in its radiant power. Chlorides of this new element² were obtained by fractional precipitation from the barium chloride. This barium chloride was extracted from a large quantity, 100 kg., of pitch blend (the residue after the removal of the uranium) obtained from the Austrian government. Although obtained only in very small quantities, a few milligrams, the chloride of this new element, called *radium*, gave about 900 times the intensity of uranium when measured by the conductivity imparted to air. Later by using still larger quantities of pitch blende, salts of radium were obtained which were still more active. So closely related is the chemical behavior of barium and radium that as yet radium has not been obtained pure, but always in some salt of barium. The proportion of radium in a barium salt may be increased by utilizing the difference in solubility of the two salts. Barium salts are more easily dissolved in pure water or alcohol.

E. Demarçay³ found that the spectrum of the barium salts containing

¹ C. R., 127, p. 1215.

² This element *radium* was independently discovered by Giesel, *Physikalische Zeitschrift*, 1, p. 16.

³ C. R., 127, p. 1218 and 129, p. 716.

radium contained quite a number of bright lines hitherto unknown, and that the brightness of these lines increased as salts that were more active were tested. One line ($\lambda = 4627.4$) was the center of a peculiar nebulous band; the other lines were all sharp. The wave-lengths of the brightest of these lines were 3814.7, 4683, 4340.6, 3649.6 and 4826.3.

Using the silver-nitrate reaction Mme. Curie¹ determined the atomic weight of the barium-radium. The radio-active salts gave values ranging from 140 to 145.8 while the inactive barium salts gave 137.7 by the same method. This indicates that the atomic weight of radium is greater than that of barium.

A. Debierne² has isolated another substance from pitchblende which is comparable in its radiant power to radium and polonium. Its radiation resembles that from radium, although it is not self-luminous like some radium salts. He has found in *actinium*, as he calls this element, all the properties possessed by radium rays. It resembles thorium in its chemical behavior so closely that he is led to suspect that the activity of thorium may be due to the presence of actinium in thorium salts.

In most of the work which has been done only very small amounts (a few mg.) of the radium or polonium-containing salts were available. Within the last few months, however, more has been available and masses of a gram or more have been used.

The radiation from the earlier radium salts was about nine hundred times as great as that from uranium, while the polonium salts gave about one-half as much as the radium salts. The salts obtained later gave an intensity 5000 to 50,000 times that from uranium. They would affect a photographic plate in half a minute where uranium required hours. The discharge³ of electricity by this radiation is comparable to the discharge by a flame and could be detected even when the rays penetrated 4 mm. of brass. The radiation, like X-rays, excites a fluorescence on a barium platinocyanide screen even through thin sheets of aluminum.

The intensity of the radiation from these salts increases⁴ for some days or weeks after solidification, the final activity being five or six times the initial. Afterwards the intensity remains practically constant as long as kept free from moisture. The activity of polonium, however, slowly falls off so that in the course of a year a considerable decrease occurs.⁵

Small temperature changes produce little effect on the radiation. Heating the salt will destroy its radiant power, but after a day or so it

¹ C. R., 129, p. 760.

² C. R., 129, p. 593 and 130, p. 906, April 2, 1900.

³ Elster and Geitel, Wied. Ann., 69, p. 83.

⁴ Mme. Curie, C. R., 129, p. 760. Giesel, Physik. Ztschr., 1, p. 16, 1899.

⁵ Curie, Science Abstracts, p. 465, 1900. Behrendsen, Ann. der Physik., 2, p. 335, 1900.

recovers a large part of it.¹ Behrendsen² found by reducing the temperature of radium to that of liquid air, that the intensity was decreased. But on restoring the salt to ordinary temperatures, the radiation was more intense than before.

Usually radium salts give greater intensity of radiation than polonium salts. Giesel obtained, however, a polonium preparation which exceeded the best radium salt which had been prepared up to that time. However, as will be seen later, the radiations from the various sources cannot be accurately compared.

FLUORESCENCE AND PHOSPHORESCENCE.

In general all substances which fluoresce or phosphoresce under the action of X-rays or ultraviolet light are excited by radium and polonium, while those which are excited by visible light are not affected by Becquerel rays. Barry,³ in testing a large number of substances, particularly the alkaline metals and earths, found that all those that were excited by X-rays were also excited by radium rays and those that were not affected by X-rays were also not affected by radium rays. Becquerel⁴ noticed some exceptions to this. A diamond that was not excited by X-rays became quite luminous under the action of radium rays. Calcium sulphide is scarcely affected by X-rays, yet it is by radium rays. Some specimens of fluorite which fluoresced strongly by ultraviolet light became nearly as luminous under the action of radium rays. This fluorite, after an exposure to radium rays, showed a visible phosphorescence for more than twenty-four hours.

Some of the radium salts are self-luminous. Giesel⁵ prepared some that without exposure to any source of light, gave a bluish light so bright that one could read by it. This luminosity is probably due to the excitation of a fluorescence of the barium salt in the radium preparation by the rays from the radium. Salts which are not self-luminous give out more intense Becquerel rays than the more luminous salts. This is to be expected, as the rays which produce the fluorescence must be absorbed by the barium salt. Salts freshly prepared gradually change their color. Some crystals prepared by Giesel⁶ were at first green, then yellow and at last brown. With the change in color the fluorescence of the salt became weaker and the Becquerel rays stronger.⁷

¹ Elster, *Verhandl. Phys. Ges.*, Leipzig, Jan. 5, 1900.

² *Ann. der Physik.*, 2, p. 335, 1900.

³ *C. R.*, 130, p. 776.

⁴ *C. R.*, 129, p. 912.

⁵ *Physik. Ztschr.*, 1, p. 16.

⁶ *Ibid.*

⁷ Also M. and Mme. Curie, *C. R.*, 129, p. 823.

Giesel¹ found that, like X-rays, radium rays produced a faint sensation of light when brought near the eyes,—even when they were closed. This sensation is probably due to a fluorescence excited within the eye itself.

Some of the Curie polonium preparations do not excite fluorescence although more active in discharging electrified bodies than some of the de Hæen preparations that give relatively strong fluorescent action.² This indicates a difference in the radiations from different salts which is confirmed in other ways.

CONDUCTIVITY OF GASES.

The radiations from the salts of uranium, thorium, polonium, radium, and actinium impart a temporary conductivity to gases. This conductivity has been studied in detail in the cases of radiations from uranium and thorium by Rutherford³ and Owens.⁴ The conductivity imparted to gases by Becquerel rays does not differ essentially from the conductivity imparted by other methods, as by X-rays, kathode rays, or flames. The results in all cases so far obtained agree with the ionization theory first suggested by Giese⁵ and Schuster⁶ and later more fully developed by Professor J. J. Thomson. This theory assumes that under the influence of X-rays or Becquerel rays some of the molecules of the gas are broken up into ions, half of which are charged positively and the other negatively. These ions may in some cases become nuclei for clusters of molecules, as in the case of the gases from flames where the ions seem to have greater mass than usual. Under the influence of electrical forces the ions move with a velocity approximately proportional to the intensity of the field. A charged body placed in the gas will therefore attract one kind and repel the other. Upon coming in contact with a metallic conductor these ions will give up their charges and cease to exist as ions. The ratio of the number of ions existing in any gas to the total number possible is very small, so that the gas when ionized by any radiation behaves like an extremely dilute electrolyte. From this it follows that the electrical current between two electrodes immersed in the gas is not always proportional to the difference of potential, that is, it does not obey Ohm's law. For small potential differences, the current will be approximately proportional to the potential difference; but for much larger potential gradients, all the ions may be used in carrying charges as fast as generated by the rays. Therefore as the cur-

¹ *Physik. Ztschr.*, **1**, p. 43, 1899.

² Meyer and von Schweidler, *Physik. Ztschr.*, p. 209, February 10, 1900.

³ *Phil. Mag.*, **47**, p. 109.

⁴ *Phil. Mag.*, **48**, p. 360.

⁵ *Wied. Ann.*, **17**, p. 538, 1882 and **38**, p. 403, 1889.

⁶ *Proc. Roy. Soc.*, **37**, p. 317, 1884.

rent increases it will approach a limit where for further increase in potential no increase of current will result.

The velocities of the positive and negative ions in various gases have been determined by several different methods. It is almost universally true that the negative has a greater velocity than the positive ion in the same electrical field. In dry air the velocity of the negative ion is about 37 per cent. greater than the velocity of the positive.¹ Rutherford determined the velocity of the ions generated by the radiations of uranium and found that they were, within experimental errors, the same as those generated by X-rays. While the method was not at all accurate for absolute determinations, it afforded a good method for comparison. As in the case of air ionized by X-rays, the negative ion moves faster than the positive ion in the same electrical field. This explains the results obtained by Beattie, who observed that the gas near uranium in an electrical field was generally positively charged. As the positive ions move through the electrical field more slowly than the negative, an excess of positively charged ions will be found in the field.

The ionization produced in a gas is proportional to the absorption of the rays by the gas. It is therefore those rays that are most strongly absorbed that will produce the greatest conductivity in a gas. The absorption of polonium rays by air is greater than the absorption of radium rays, so that for the same intensity polonium rays will produce greater ionization. The discharging action of Becquerel rays from different sources is therefore not a true measure of their intensities. The radiation from these various substances is also known to be non-homogeneous in character. For example, Rutherford has found that the radiation from uranium may be classified in two groups, α and β rays. The α rays produce relatively a greater amount of ionization than the β rays. It is thus seen that any measurements of the relative intensities of Becquerel rays from different sources by the conductivity they impart to the air is liable to considerable error. It may be likened to the measurements of the intensity of the different sources of visible light by a method which really measured the intensity of one color only, as, for example, green. The same objection can be made to photographic or fluorescent methods.

The effect of Becquerel rays on a spark gap has been tested by Elster and Geitel.² When a spark gap, 1 cm. long, consisting of a positive knob and a negative disc, was exposed to these rays, the spark or brush discharge was changed into a glow discharge. The spark gap was found to be very sensitive to the presence of the rays. The electrodes did not need to be polished as in the case of ultraviolet light.

¹ Zeleny, *Phil. Mag.* 46, p. 120; *Proc. Roy. Soc.* 66, p. 238, March 1, 1900.

² *Wied. Ann.*, 69, p. 673.

ABSORPTION.

By measuring the absorption of uranium rays by different numbers of thin plates, Rutherford concluded that uranium rays were not homogeneous, but could be divided into two classes, α rays and β rays. The β rays were much more penetrating than the α rays. Relatively greater ionization is produced by the α rays, as they are more strongly absorbed by gases. The α rays therefore appear to be the more intense, as measured by the conductivity imparted to gases. As a result of this composite character, the absorption of Becquerel rays from uranium does not obey the ordinary law of absorption. A thin sheet of metal or a sheet of paper reduces the intensity considerably, but as the number of layers is increased their relative effect decreases. The first layers absorb the α rays, which apparently are the most intense, and additional layers affect only the β rays, which are more penetrating. Aluminium foil, 0.002 cm. thick, reduced the intensity to about $\frac{1}{20}$ of its original value. But an additional thickness of 0.05 cm. only reduced the intensity to about one-half of the intensity transmitted through 0.002 cm. Rutherford's results indicate that the β rays are homogeneous. Their penetration is comparable to that of X-rays from an ordinary Crookes' tube. X-rays from the modern "hard" tube are however much more penetrating. The α rays have about the same penetrative power that "secondary" X-rays have. Since the α rays are the most active in producing ionization and the β rays have the greatest photographic action, determinations by these two methods of the absorption of uranium rays by different substances give results which do not agree. The α rays appear to come from the surface, while the β rays seem to come from the interior. Thus the radiation from a thin layer consists chiefly of α rays, while the proportion of β rays is increased if the radiation is from a thick layer.

The radiation from thorium¹ is in general more penetrating than uranium rays when measured by the conductivity imparted to gases. Schmidt² found that the absorption of thorium rays by a number of layers of metal was less than the sum of the absorption by the layers taken separately. This shows that these rays too are not homogeneous. However Mme. Curie³ noticed a difference between the radiation from thin and thick layers of the thorium compound. Owens⁴ found that the radiation from thin layers was homogeneous, and that the radiation from layers a millimeter or more in thickness was not homogeneous.

Owens showed that the absorption of thorium rays by gases followed the order of the gas densities.

¹ Mme. Curie, C. R., 126, p. 1101 and Rutherford, Phil. Mag. 47, p. 123.

² Wied. Ann., 65, p. 141.

³ C. R., 126, p. 1101.

⁴ Phil. Mag., 48, p. 360.

Becquerel¹ observed, while obtaining fluorescence of different substances by radium rays through absorbing screens, that the screens affected the fluorescence in some salts more than it did in others. The simplest explanation of this is that the radiation from radium is also not homogeneous in character. This is confirmed by the researches of Meyer and von Schweidler² who found, as in the case of uranium and thorium, that the absorption of radium rays by quite a number of substances did not obey the ordinary absorption law. Using the rate of discharge of an electrified body as a measure of the intensity they found that a thin layer of metal diminished the intensity greatly, but additional layers produced but little effect. Through a thin sheet of platinum, 0.0025 mm. thick, 49 % of the original intensity was transmitted, while two such sheets let through 36 % and a layer, 0.12 mm. thick, gave 15 %. 28 % was transmitted through one sheet of aluminium, 0.16 mm. thick, while 16 % was transmitted through six sheets. A sheet of tin, 0.011 mm. thick, transmitted 44 %, two sheets 31 % and fifteen sheets 15 %. 38 % penetrated one sheet of paper, 0.06 mm. thick, and 20 % twenty-two sheets. Glass of 0.16 mm. thickness, transmitted 26 % and ten plates 16 %. Similar effects were obtained through quite a number of other metals and substances. These results were obtained with the radiation from a radium barium carbonate prepared by M. and Mme. Curie. The rays from a bromide and a chloride of radium prepared by Giesel behaved similarly, but were less penetrating than the rays from the salt obtained from the Curies.

As has been shown, the radiations from uranium, thorium and radium consist of at least two kinds of rays, one which is greatly absorbed and another which is far more penetrating. R. J. Strutt³ has found that the absorption of the more penetrating component of radium rays depends only on the density and thickness of the absorbing substance. The absorption by various substances, ranging in density from that of platinum, lead and silver, to that of aluminium, paper and sulphur dioxide, follows the same order as their densities. He further showed that within a reasonable approximation, the quotient of the coefficient of absorption divided by the density is a constant. This is the same law observed by Lenard⁴ in the case of cathode rays. The absorption however was about five hundred times greater in the case of cathode rays.

Polonium rays seem to correspond to the less penetrating rays of radium, being readily absorbed by all substances. While rays have been obtained⁵ from radium which have penetrated 1 to 2 cm. of metal, polonium rays are greatly absorbed by paper and card board. Giesel said that

¹ C. R., 129, p. 912.

² Physik. Ztschr., 1, p. 209.

³ Nature, 61, p. 539, 1900.

⁴ Wied. Ann., 56, p. 255.

⁵ Giesel, Physik. Ztschr., 1, p. 16.

polonium rays gave better radiographs of the hand as they showed more contrast. However these radiations will probably never be found very useful in surgical work owing to the strong absorption of them by air and light substances. A few centimeters of air will totally absorb the rays from the polonium prepared by M. and Mme. Curie, while rays from radium sufficiently intense to excite a fluorescent screen have been obtained through 40 or 50 cm. of air.

Mme. Curie¹ noticed that the absorption of the rays from their polonium increased as the distance from the source is increased. They will penetrate a very thin aluminium plate, but their penetrative power is decreased thereby. Or as it may be stated, the coefficient of absorption increases with increase of the thickness of the absorbing medium. These rays seem to behave like small projectiles which rapidly lose their velocity and therefore their penetrative power.

Evidence of a feeble but more penetrating radiation from radium closely resembling X-rays has been recently found by Villard.²

CHEMICAL EFFECTS.

M. and Mme. Curie³ found that the glass of bottles in which radium salts had been kept for some time turned violet and then black. The effect seems to gradually penetrate through the glass. Villard⁴ noticed the same effects with X-rays. He said that a radiograph can thus be obtained on glass by a sufficiently long exposure to X-rays. This coloring of the glass has also been observed with kathode rays. Giesel⁵ found that rock salt or potassium bromide when exposed to radium rays for a day took the same coloring that kathode rays give them. M. and Mme. Curie noticed that a barium platinocyanide screen was fatigued by the impact of radium rays in the same way that it is fatigued by kathode rays. Radium rays act in many ways like light, reducing silver salts, peroxide of iron and bichromate of potash in the presence of organic substances. Besides coloring glass they will also color porcelain and white paper.⁶

The radiation from radium salts seems to convert oxygen into ozone. This was first noticed by Demarçay, to whom M. and Mme. Curie had sent some radium salt in a tightly stoppered bottle. On opening the bottle, the characteristic odor of ozone was distinctly noticeable. A coloring of a mixture of starch and potassium iodide,⁷ a common test for

¹ C. R., 130, p. 76.

² C. R., 130, pp. 1010 and 1178.

³ C. R., 129, p. 823.

⁴ C. R., Nov. 27, 1899.

⁵ Verhandl. Phys. Ges., Leipzig, Jan. 5, 1900.

⁶ Science Abstracts, p. 465, 1900.

⁷ M. and Mme. Curie, C. R., 129, p. 823.

ozone, was obtained. Giesel, however, failed to detect the formation of ozone by any of the salts he had.

In the course of time the radio-active salts undergo changes of structure. This is quite noticeable in some of the radium barium salts which change color for several days after they are made. A greenish yellow barium platinocyanide screen prepared from barium salts containing radium was observed by Giesel to be at first yellow then orange and finally a brownish red. A single one of these crystals will appear a clear yellow but on crossing two of them only brown red light is transmitted. The same effect is noticed when one of these crystals is tested with a Nicol. The usual barium platinocyanide salts as well as the freshly prepared active salts show no such polarization.

SECONDARY OR INDUCED ACTIVITY.

Sagnac² discovered that X-rays had the power of giving to bodies on which the rays impinge the ability to radiate rays which are called "secondary" rays. The action of these secondary rays ceases the instant the X-rays are cut off from the excited substance. As Becquerel rays seemed to be similar in action to X-rays, it was therefore natural to expect such rays in this case. M. and Mme. Curie³ found that the rays from radium were apparently able to induce in other substances such as zinc, platinum, bismuth and even paper the temporary power of emitting Becquerel rays. These secondary rays were readily detected by the conductivity they imparted to gases even after the removal of the radium. Increasing the length of exposure to radium rays increased the acquired activity. On removal of the radium the induced radiation rapidly decreased, in two or three hours being reduced to about one-tenth. The secondary activity induced in the different substances varied from one to fifty times the intensity of the radiation from uranium. An explanation of this phenomenon is readily suggested. If the radium gives off a vapor or something similar to a fine dust, some of it may be deposited on neighboring substances. Each of these small particles may give off Becquerel rays, but owing to its small size it is unable to keep up this output of energy. However, it was found that the induced activity could not be destroyed by washing. And as the radium rays would produce this effect through thin sheets of aluminium, they felt confident that it could not be due to the presence of a vapor or to traces of the radium salt on the substance. It seemed to be more allied to a phosphorescence. However, if it were a real induced effect, differences should be detected in the activity excited in different bodies, as is the case with secondary

¹ *Verhandl. Phys. Ges.*, Jan. 5, 1900.

² *C. R.*, 125, pp. 573 and 942, also 126, p. 521.

³ *C. R.*, 129, p. 714.

X-rays. But no such difference was observed, all substances apparently showing the effect equally.

Becquerel¹ observed that this activity was induced in pieces of the fluorite which showed such intense phosphorescence. After an exposure to radium rays it was able to discharge electrified bodies. However, the acquired activity could be destroyed by heating or by washing with water. This is contradictory to the results of M. and Mme. Curie. He further found that although this activity, which was acquired by many different substances, could discharge electrified bodies, it could not affect a photographic plate.

Elster and Geitel² while freeing some radium salts from water in a vacuum tube found that a cold glass body brought into the tube became coated with a scarcely visible deposit. This glass body was then found to emit rather intense rays. At first they thought that they had a case of the induced activity similar to that announced by M. and Mme. Curie, but they found that this activity could be destroyed by washing. These results of Becquerel and Elster and Geitel, together with the work of Rutherford on thorium, to be referred to later, make it quite probable that some of these salts, in addition to emitting Becquerel rays, send out very small particles, perhaps of molecular dimensions, which retain for a time the ability to give out these rays. Rutherford³ has in the case of thorium found very strong reasons in support of this view. He has found that these small particles can apparently penetrate screens of paper and thin sheets of metals.

It now seems probable that Becquerel rays are similar in character to cathode rays, that is, are small particles of matter carrying negative charges and moving at a high velocity. By some writers it has been thought necessary to explain the apparent penetration of thin screens of metal by assuming that when a particle strikes one side another particle on the opposite side is in some way driven off. Hence if cathode rays impinge on one side, new rays are emitted on the opposite side, giving the metal screen the appearance of transparency. Following this line, Villard⁴ has attempted to show that in the case of radium rays the apparent penetration is due to secondary rays which are emitted by the opposite face. These secondary rays are of an entirely different nature from the induced rays of Curie or Rutherford. They cease the instant the incident radiation is suppressed. Villard thought that he had proven that the chief radiation beyond a screen started from the screen itself going in a path perpendicular to its surface. While under some circumstances the sec-

¹ C. R., 129, p. 912.

² Verhandl. Phys. Gesell., Leipzig, Jan. 5, 1900.

³ Phil. Mag., 49, pp. 1 and 161.

⁴ C. R., 130, p. 1010.

ondary emission from screens may be the predominate one Becquerel¹ denies that it is always so. He found evidences that some of the rays passed directly through, accompanied, however, by a diffuse radiation from the screen. With thick screens, or thin ones placed obliquely, the secondary rays are relatively more intense, but for thinner screens they become less important.

The secondary rays may differ from the incident beam, but to what extent is not known. Different observers disagree. Dorn² says that the rays from the salt consist chiefly of rays which are not deflected by a magnet but are transformed by a screen into deflectable rays. Villard³ says that secondary rays are produced by the deflectable rays and always leave the screen perpendicularly. Becquerel thought that part of the secondary rays could not be deflected while the rest could.

THORIUM "EMANATIONS."

Mme. Curie⁴ noticed that the radiation of thorium from thick layers was apparently more penetrating than from thin layers. This was confirmed by Owens⁵ who also observed that the radiation from thick layers of thorium was greatly affected by slight air currents. Rutherford⁶ has taken up the subject and has found that thick layers, one millimeter or more, of thorium oxide and other thorium compounds seem to have the property of giving off small particles which can radiate Becquerel rays for a time. This vapor or "emanation," as Rutherford calls it, can pass through very thin sheets of metals and through many layers of foolscap paper. It gradually diffuses itself through the air and may be carried away by light currents. When the "emanation" is drawn by a current of air into the space between two metallic plates, one of which is connected to a sensitive electrometer, the intensity of its radiation may be measured by the electrical current which will pass through the gas. It was found by this method that the electrical discharge would last about ten minutes after the air current is stopped. If the conductivity had been due to the ordinary gas ions brought over from the neighborhood of the thorium, it would have lasted for only a second or so. For considerable potential differences, the ions that carry the charges in the conduction in gases, are used and thus destroyed as rapidly as they are produced. Rutherford, however, found that the rather slow decay of the electrical current after the air motion had stopped, was independent of the potential difference employed. This too contradicts the supposition that ions alone were present, for in this case for large potential differ-

¹ C. R., 130, pp. 979 and 1154.

² Beiblätter, p. 572, 1900.

³ C. R., 130, p. 1010.

⁴ C. R., 126, p. 1101.

⁵ Phil. Mag., 48, p. 360.

⁶ Phil. Mag., 49, pp. 1 and 161.

ences the ions would be used up immediately. It seems evident that there must be something in the air between the plates of the condenser which, by sending out Becquerel rays, made the air conducting. Air containing these emanations could be drawn through wool or bubbled through water, dilute or strong sulphuric acid, without destroying the emanations. Ions are destroyed by such processes. The emanation is also independent of the nature or pressure of the gas surrounding the thorium.

Rutherford found that under certain conditions this emanation has the property of making other bodies radio-active. Any substance, charged to a negative potential, will become able to emit Becquerel rays after it has been kept for a few hours near thorium or in contact with air containing the emanation. By keeping a wire exposed to air containing the emanation, negatively charged, the radio-activity may be concentrated on it instead of being distributed over the neighboring surfaces. Bodies made active in this manner will retain this property for several days. Rutherford showed that this induced activity could not be due to the direct radiation of the thorium rays or to any ordinary dust from the thorium.

It seems probable that the small radio-active particles which diffuse from thorium in some way take on a small positive charge. The particles will then be attracted by negatively charged bodies. In this way a body may become partially coated with this active material. It was found that the activity which ordinarily would last for several days could be removed by a long and vigorous polishing with sand paper. On placing a very active platinum wire in sulphuric acid, the radio-activity was largely destroyed. The residue of the acid obtained by boiling it down on a sand bath was then found to be strongly active.

The radiation from the different bodies that had been made active, differed from thorium radiation. It was in some cases more intense, as when the activity was concentrated on a negatively charged wire. It was more penetrating than the radiations from any of the uranium, thorium, polonium, or radium compounds which he had been able to test. If this activity is due to the presence of a radio-active substance, its power per unit mass of emitting Becquerel rays is large as compared to that of thorium.

Debiere¹ has recently found a very active element, actinium, which so closely resembles thorium in its chemical behavior that he thinks the activity of thorium is in part, at least, caused by the presence of this element. He points out that the experiments of Rutherford can be explained by the presence of this element as an impurity.

Rutherford thinks that the reason the vapor particles are attracted by a

¹ C. R., 129, p. 593, and 130, p. 906, April 2, 1900.

negative charge is due to the fact that they become positively charged by the diffusion of the ions in the gas. As negative ions are known to move more rapidly than the positive they tend to leave the gas with an excess of positive ions. M. and Mme. Curie have proven that some radio-active substances tend to become positively charged since negative charges are carried off by the rays. In this way the presence of a slight positive charge on the active particles which diffuse from thorium may be explained.

Attempts to obtain this emanation or something similar to it from uranium, polonium, and radium have failed. Rutherford's specimens of radium and polonium were, however, not pure. S. Meyer and E. R. Schweidler¹ observed that when a radium barium carbonate prepared by M. and Mme. Curie was removed from a metallic cylinder within which it had been kept, the air within the cylinder retained its conductivity for some time. But radium salts prepared by Giesel did not show this. These facts, together with the induced radio-activity observed by M. and Mme. Curie, suggest that possibly some of the radium salts give off a vapor similar to that observed from thorium.

MAGNETIC DEFLECTION.

Elster and Geitel² observed that the discharge by Becquerel rays of an electrified body in a vacuum tube was retarded by a magnetic field. Two explanations at once suggest themselves: the effect may be due to the deflection of the rays by the magnetic field, or, as in the case of discharge by ultra-violet light, part of the ions may be deflected back on the charged body. Attempts by them to observe a direct magnetic deflection of the radium rays were at first failures. This failure was probably due to the nature of the salt used as well as the method. Later a magnetic deflection was observed almost simultaneously by S. Meyer and E. R. v. Schweidler,³ Giesel,⁴ and Becquerel.⁵ It has since been verified by Elster and Geitel⁶, Warburg⁷ and M. and Mme Curie⁸ and several others. In all cases the deflection is in the same direction as for kathode rays, *i. e.*, in the direction corresponding to the deflection of a negative current.

The deflection is not obtained with the rays from all the salts of radium and polonium. Meyer and Schweidler failed to find it with the rays from

¹ Physik. Ztschr., p. 209, Feb. 10, 1900.

² Wied. Ann. 69, p. 83.

³ Physik. Ztschr., Nov. 25 and Dec. 2, 1899.

⁴ Wied. Ann., 69, p. 834, Dec., 1899.

⁵ C. R., 129, p. 996, Dec. 11, 1898.

⁶ Verhandl. Deutsch. Phys. Ges., Leipzig, Jan. 5, 1900.

⁷ Ibid.

⁸ C. R., 130, pp. 73 and 76.

a radium barium carbonate and a polonium nitrate. Both Becquerel and M. and Mme. Curie failed to find any deflection of the rays from any of the polonium salts prepared by M. and Mme. Curie. Rays from some polonium prepared by Giesel have been deflected.¹ This has led to a classification by M. and Mme. Curie² of the rays under two heads, the rays deflectable by a magnetic field, and those not deflectable. Many salts of radium give off both kinds. This classification corresponds to that already given under the head of absorption. The more penetrating rays of radium are the deflectable ones, while the less penetrating ones are not deflectable. The rays from the polonium prepared by M. and Mme. Curie are not deflectable, and they do not contain any of the more penetrating type. M. and Mme. Curie³ have found that the non-deflectable rays of radium behave like the rays from their polonium. As measured by the conductivity imparted to air the penetrating or deflectable rays of radium are a small fraction of the total radiation. However, the less penetrating rays are almost totally absorbed by 7 cm. of air, so that at even small distances from the source the penetrating rays are in excess. Debierne⁴ has shown that the rays from actinium belong to the deflectable class. Thorium rays have not as yet been deflected.

Becquerel⁵ has recently obtained a magnetic deflection of uranium rays. It has been thought that part at least of the radiation from uranium is due to the presence as an impurity of actinium. Becquerel attempted to remove the actinium from the uranium salt. This decreased the activity of the uranium and the foreign substance extracted was found to be active. As the radio activity of uranium was not entirely destroyed, Becquerel thinks that uranium has a radiation of its own. The deflectable and the more penetrating rays, β rays, of uranium are probably due to actinium.

The usual method of observing the magnetic deflection is to place the radiant substance on a photographic plate or on a fluorescent screen. The radio-active salt is placed in a hole in a little block of lead so that the rays are emitted only in a direction perpendicular to the plate or screen. When the field is excited to about 2000 C. G. S. units the rays are

Fig. 1.

¹ Elster and Geitel, Meyer and Schweidler, and Giesel.

² C. R., 130, pp. 73 and 76.

³ Ibid.

⁴ C. R., 130, p. 906.

⁵ C. R., 130, p. 1585, June 11, 1900.

deflected in a circular path and fall on the plate or screen on one side of the radio-active substance. As used by Meyer and v. Schweidler, the substance *B* (see figure) is placed below a fluorescent screen. With no magnetic field the rays travel rectilinearly away from *B* exciting luminosity only on a spot directly above *B*. When a uniform magnetic field, perpendicular to the plane of the figure and in direction away from the observer, is created, two luminous spots will appear, *D* and *E*. An opaque screen placed above *B* will cause the spot *E* to disappear. When placed below *B* it will affect *D*, or when placed below *E* no effect is observed. In this way the path of the rays is readily traced.

When the rays are perpendicular to a uniform field they move in arcs of circles, but when the direction is not perpendicular to the field, or the field is not uniform, the path is more complex. In all cases the action is similar to that observed with cathode rays. Becquerel found that when the direction of the rays was not perpendicular to the field the path became a spiral. If the field were not uniform the rays could be concentrated or focused by it.¹ For example, if the radium salt be placed on or near one pole face of an electromagnet of the horseshoe type and a screen placed near the opposite one, the diffuse illumination of the screen could be concentrated by the field to the part nearest the pole piece. This requires an electromagnet of rather small pole pieces.

These effects are all readily explained if we assume that the rays are, as is now generally conceded in the case of the cathode rays, small particles carrying negative charges.

Until the determination of the magnetic deflection of Becquerel rays, the known phenomena of these rays were almost identical with those of X-rays. The discovery of the magnetic deflection of Becquerel rays led Strutt² to make a further attempt to deflect X-rays. By carefully arranged apparatus he was able to assert that if there were a deflection, the radius of curvature of the path was greater than 19,800 cm., in a field of 3270 C.G.S. units. With this field the radius of curvature of Becquerel rays was about a centimeter.

If the deflectable Becquerel rays consist of rapidly-moving negatively charged particles, it may be shown that

$$m \frac{v^2}{\rho} = Hev$$

or

$$\frac{e}{m} = \frac{v}{H\rho},$$

where e/m is the ratio of the charge to the mass of the particle, v its velocity, H the strength of the magnetic field, and ρ the radius of curvature of the path of the rays. It has been observed by several that the rays

¹ Becquerel, C. R., 129, p. 912, also Meyer and v. Schweidler, *Physik. Ztschr.*, 1, p. 113.

² *Proc. Roy. Soc.*, 46, p. 75.

are not equally deflected. Becquerel¹ found that in the radiation from a single sample of radium the value of $H\rho$ varied from about 350 to nearly 3,000. As is evident, a magnetic spectrum of Becquerel rays is always produced with a source that gives such a non-homogeneous radiation. The values of $H\rho$ are of the same order of magnitude as in the case of cathode rays.

That different parts of this spectrum have different properties is readily shown by its penetrative power. Those rays which are deflected the most will penetrate only very light bodies or very thin sheets of paper and aluminium foil. For the portion of the spectrum corresponding to a small deflection the rays will penetrate thicker or denser metals. The penetrative power increases as the deflection decreases. Or for those rays for which $\frac{e}{mv}$ is smaller the penetration is greater. This is what would be expected if the difference in the rays is due to a difference of velocity of the charged particles, since the particle with the greater velocity is more penetrating and is also less deflected by the field. To observe this difference in absorption, Becquerel laid side by side on a photographic plate long narrow strips of the different metals. The direction of the strips was parallel to the direction of the dispersion. In this way it was easily shown that the thin strips of the lighter materials let through almost the entire spectrum, while the denser strips let through only the part deflected the least.

From Becquerel's observations may be deduced, at least approximately, that the amount of spectrum transmitted by different substances of the same thickness, follows the inverse order of their densities. This is in confirmation of the view that the difference in deflection is caused by a difference in velocity of the particles. Following this hypothesis of small particles, the non-deflectable or less penetrating rays are probably particles of much greater mass. Whether these particles are charged or not is not certainly known, as the deflection of larger particles may be so small as to have escaped detection.

Becquerel² found that an absorbing screen placed near the source permitted rays giving greater deflection to pass through than when the screen is placed farther from the source. Others³ have noticed that the absorption of a screen increases with the distance from the source. This may be explained in two ways. The penetrating power of the rays seems to depend on their velocity. If the velocity is decreased by passage through the air then the rays have less penetrative power at greater distances from the source. Or, the apparent transmission may be

¹ C. R., 130, p. 372.

² C. R., 130, pp. 372 and 979.

³ See C. R., 130, p. 979.

largely due, as some writers think, to a secondary radiation emitted by the screen. This secondary radiation may travel at a different velocity and may be deflected more than the incident beam.

Becquerel¹ tried in several ways to find out if the velocity was altered by transmission through air or other substances. Any change in velocity should be detected by a change in the magnetic deflection. Although unable to settle the question positively, as the experimental difficulties are rather great, he could detect no change in the velocity or rather in the ratio

$\frac{e}{mv}$. Some experiments on this subject are misleading. Becquerel² ob-

tained a magnetic deflection in a vacuum and then in air. Measurements showed them equal. But he protected his plates with black paper. As he has since pointed out, if the rays which penetrated the paper in a vacuum had their velocity diminished in air, their penetrative power would be decreased, and although deflected more the photographic plate would not show it as they could not then penetrate the paper. The great difficulty in determining any change in the velocity is due to the many different velocities present, and an inability to distinguish them. In this connection it may be stated that no change in the velocity of kathode rays has been observed when they have penetrated screens.

ELECTROSTATIC EFFECTS.

If the deflectable rays carry negative charges they should, as is the case with kathode rays, give negative charges to bodies which they strike, and should be deflected by an electrostatic field. At first³ no such effects were obtained. As the rays make the surrounding air a conductor, any negative charge imparted to a body will be conducted off by the air. This conductivity of the air also makes a deflection of the rays by an electrical field difficult to observe, since the air being a conductor tends to serve as an electrostatic screen.

There seem but two ways open to detect the negative charge imparted to a body struck by the rays. If the body be enclosed by a very high vacuum it can then retain its negative charge. This may be varied by placing the radium salt in the vacuum, where it will accumulate a positive charge. The second method is to entirely enclose either the target or the radium itself in a solid dielectric like paraffin or ebonite. One side of this dielectric should be thin enough to permit the rays to traverse it. Using this latter method M. and Mme. Curie⁴, with a sensitive electrometer, observed not only that the rays carried with them negative

¹ C. R., 130, p. 979.

² C. R., 130, p. 206.

³ Becquerel, C. R., 129, pp. 1205 and 130, p. 206.

⁴ C. R., 130, p. 647.

charges, but also that the rays by carrying away a negative charge left a positive charge on the radium. The rate at which a negative charge was carried off by the rays as measured in amperes was 4×10^{-12} per sq. cm. of the radium salt.

E. Dorn¹ was the first to obtain a deflection of Becquerel rays by an electrostatic field. The rays used were those from a bromide of barium and radium. Lenard² found that the excitation of a fluorescent screen by the impact of kathode rays could be either increased or decreased by an electric field parallel to the direction of the rays. When the field accelerated the charged particles the fluorescence was increased. Reversing the field produced a diminution. Dorn repeated this experiment, using radium rays instead of kathode rays, and obtained the same results as Lenard.

Becquerel³ independently obtained an electrostatic deflection of the rays. Although he used an intense electrical field of about 10,000 volts per cm., the deflection observed on the photographic plate was only 4 mm. Hence it was necessary to use a very narrow beam of rays such as obtained through a narrow linear slit. In the path of this narrow beam was placed a thin screen, mica covered with tin, parallel to the linear source and edge on, so that its shadow on the plate was linear. By deflecting the beam at right angles to this shadow a broadening of it was obtained. As in the case of magnetic deflection it was observed that the rays were unequally deflected, again showing their composite character.

Knowing the field strength and the amount of the deflection the value of mv^2/e is obtained. Since mv/e is obtained from the magnetic deflection both the velocity and the ratio of charge to mass may be computed. The difficult thing is to identify in the two spectra the corresponding radiations. By observing the parts of the two spectra which seemed to show the same penetration he obtained the values for e/m and v ,

$$\frac{e}{m} = 10^7, \quad v = 1.6 \times 10^{10} \text{ cm.}$$

The ratio of charge to mass and the velocity are therefore of the same order of magnitude as in the case of kathode rays. These values can be regarded only as approximations. The velocity according to the above figures is about one-half the velocity of light. The measurements of Dorn on the deflection by an electric field agree in magnitude with Becquerel's measurements. Using the value of the current obtained by M. and Mme. Curie, which is equal to Nv , where N is the number of particles given off

¹ *Abh. d. Nat. Ges. zu Halle*, March 11, 1900, also *Physik. Ztschr.*, p. 337, May 5, 1900.

² *Wied. Ann.*, 65, p. 509, 1898.

³ *C. R.*, 130, p. 809.

in one second, and the observed value of mv^2/e , $\frac{1}{2} Nmv^2$ or the energy per second of the radiation is obtained.

$$Ne = 4.10^{-12} \text{ amperes or } 4.10^{-13} \text{ C. G. S. and } mv^2/e = 2.57 \times 10^{13}.$$

Then $\frac{1}{2} Nmv^2 = 5.1$ C. G. S. units. Or the energy emitted per second per square cm. is about five ten-millionths of a watt.

From the above ratio of e/m and the current the mass of the particles carried off in a second may be computed. This amounts to about a milligram in a thousand million years.

THEORIES.

Many theories have been suggested concerning the origin of the energy of the Becquerel radiation. Mme Curie¹ first suggested that the energy may be due to a very penetrating radiation hitherto unknown which could excite fluorescence in some substances. Sir William Crookes suggested in the Presidential address before the British Association in 1898 that in some way the energy might be obtained from the rapidly moving air particles. Elster and Geitel² took a salt of uranium into a deep mine, where it was protected by 850 meters of earth from any external radiations, and the salt was still active. When kept in a high vacuum the radiation was still emitted, so that the energy cannot be due to either a mechanical or chemical action of the air. They found that the impact of X-rays or kathode rays on the radiant substance produced no change in its radiation.

Elster and Geitel³ suggested that the energy may come from an unstable molecule gradually passing over into a stable state. This idea was supported also by Behrendsen.⁴ Until the discovery of the magnetic deflection of Becquerel rays many of the investigators had come to the conclusion that these rays were X-rays of feeble intensity. As the rays belonging to the deflectable group are now known to carry negative charges, they probably consist of small particles of matter, matter and electrical charges being, according to our experience, inseparable. According to the theory used to explain the Zeeman effect, each molecule has revolving around it at a high velocity one or more small satellites negatively charged. Measurements based on this theory have shown that the ratio of the charge to the mass, e/m , of a satellite is of the same order of magnitude as that obtained for the kathode ray particle or for the deflectable Becquerel rays. In the molecular groupings of the radioactive elements there may be conditions of instability such that some of

¹ C. R., 126, p. 1101.

² Wied. Ann., 69, p. 83, 1899.

³ Beib., p. 443, 1899.

⁴ Wied. Ann., 69, p. 220.

these satellites could be lost from their molecules, and moving off with their high velocity become the deflectable Becquerel rays.

The theory that Becquerel rays consist of extremely short ultra-violet light waves is now almost abandoned. In the case of the deflectable rays it is entirely dropped and it is believed that they, like cathode rays, are negatively charged particles of matter moving at extremely high velocity. Radiations of this character may differ among themselves in the size of the charge, the mass of the particles and their velocity. J. J. Thomson has shown that the ratio of charge to mass for the negatively charged particles in gases at low pressures is a constant. This together with results obtained from the Zeeman phenomena indicate that the ratio of charge to mass in these small particles is always a constant. If this is true it is the velocity which varies. The difference in penetration of Becquerel rays and cathode rays is then readily explained by a greater velocity for the Becquerel ray particle. The measurements of mv/e by Becquerel give values ranging approximately from 400 to 3000. The upper limit is higher than obtained by cathode rays and as it is the rays that give the larger values which are the more penetrating, it is safe to assume that the more penetrating rays have a greater velocity than cathode rays.

All results indicate that the atomic charge e is invariable and as in the case of the negative ion in the cathode ray or ultraviolet light discharge one infers that the mass m of the particle is much smaller than an atom, being only about one-thousandth of the size of the hydrogen atom or the ion found in electrolysis.

A theory of X-rays which is now gaining in popularity is that they are the small cathode ray particles after they have lost their charges. The absence of a charge accounts for the greater penetration. On this basis one might expect to obtain X-rays from radium rays. Villard¹ has detected the presence of such a radiation, an effect being obtained through 1 cm. of glass. This has as yet not been confirmed.

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¹C. R., 130, p. 1010, April 9, and p. 1178, April 30, 1900.