

# J. J. Thomson's Early Work on Electric Discharge through Gases, 1882-1899

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## J. J. Thomson의 초기 기체 방전 연구, 1882-1899

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### 요 약

J. J. Thomson (1856-1940) 이 캐번디쉬 연구소의 소장이 되어 실제로 실험을 하기 시작한 1884년 이래 일관되게 자신의 실험 연구의 주제로 삼았던 것은 기체방전 현상이었다. 바로 이 기체방전 실험을 통해 그는 기체전도 이론을 정립하고 '전자를 발견'했으며 20세기 초에는 양극선에 대한 연구를 수행했다. 1906년에는 기체의 전도성에 대한 연구업적이 인정되어 노벨상을 수상하였다.

이 논문에서 필자는 톰슨의 기체방전 연구 기간 중 비교적 초기인 1882년부터 1899년에 이르는 약 20년간의 연구를 살펴 본다. 기체방전에 대한 톰슨의 관심은 vortex 이론에서 비롯되었다. 기체방전 현상은 두 개의 vortex 고리 원자로 이루어진 분자가 외부로부터 교란을 받아 분해되었다가 급히 재결합할 때 나타나는 현상이라고 톰슨은 생각했다. (-1884) 이러한 vortex 이론은 톰슨이 캐번디쉬 연구소의 소장이 된 후 몇 년간 수행했던 기체방전 실험의 이론적 기반이었다. (1884-1889) 그러나 1890년 이후 기체방전 현상과 전기분해 현상간의 유비관계에 주목하게 되면서 톰슨은 전기분해의 경우처럼 기체방전에서도 물질 분자가 '분해'되어 전하를 띤 원자를 형성하는 것이 전도의 필수조건임을 깨닫게 되었다. 그렇다면 전기분해 현상과 마찬가지로 기체방전 현상도 전기적 현상과 물질의 화학적 변화와의 관계, 더 나아가 물질과 전기간의 관계라는 보다 근본적인 문제를 해결할 수 있는 유망한 연구주제라고 생각하여, 이를 자신의 실험 연구의 주요 주제로 삼게 되었던 것이다. (1890-1895) 린트젠 선의 발견 이후 'corpuscle'이 도입되면서 전도 (conduction)는 분자가 아니라 원자 자체가 쪼개져서 생기는 보다 작은 입자에 의해 일어나는 것임이 밝혀지게 되었다. (1895-)

이상의 논의를 통해, 톰슨은 1882년 경부터 물질과 전기간의 관계를 밝히려는 일관된 생각을 가지고 연구를 수행했으며 캐번디쉬 연구소의 소장이 된 이후의 연구과정은 실험과 이에 따른 이론적 사색을 통해 이 생각을 구체화, 정교화해 나가는 과정이었음을 알 수 있었다. 1897년에 'corpuscle'을 발견한 후에도 톰슨은 이를 주로 물질의 이온화, 즉 물질이 전기를 띠게 되는 현상을 설명하는 데 적용하였다.

## I. Introduction

"Discharge of electricity through gases" was the consistent topic of J. J. Thomson's experimental research since 1884, when he was appointed as director of the Cavendish Laboratory and began experimental research actively. The research occupied an important part of his life, which is shown in his reflection that "..... since then there has, I think, never been a time in which I have not had some experiments in hand on that subject."<sup>1)</sup> Through these experiments on gas discharge, Thomson could establish the theory of conduction through gases, 'discover the electron' and carry out the research on positive ray in the early twentieth century. In 1906, he won the Nobel Prize of physics for the research on gas conductivity.

The historians of science, however, had not taken sufficient interest in gas discharge which was the main topic of Thomson's experimental research. Thus far, most researches on Thomson have dealt with his atomic model, its relation to Rutherford's and Bohr's atomic models and the periodicity of the elements, centering around 'the discovery of the electron' in 1897 and his research after that.<sup>2)</sup> Even the researchers who dealt with the period preceding the discovery of the electron in 1880s and early 1890s paid attention only to Thomson's mechanical explanation based on the Lagrangian formulation of mechanics and his vortex-atom model.<sup>3)</sup>

Unlike these researchers, Isobel Falconer presented results of a comparatively detailed study on Thomson's work from 1880s to early 1890s, which was a part of her more comprehensive research program on Thomson's gas discharge experiments and related theoretical considerations conducted over the whole period.<sup>4)</sup> She pointed out that Thomson's search for unity in science and nature had motivated him to take interest in gas discharge phenomenon.<sup>5)</sup> That is to say, Thomson came to be

1) J. J. Thomson, *Recollections and Reflections*(New York : Macmillan Company, 1937) (hereafter, abbreviated as *Recollections*), p. 118.

2) J. L. Heilbron, "The Scattering of  $\alpha$  and  $\beta$  Particles and Rutherford's Atom," *Archive for History of Exact Sciences* 4(1968), 247-307; "J. J. Thomson and the Bohr Atom," *Physics Today* 30(1977), 23-30.

3) David R. Topper, *J. J. Thomson and Maxwell's Electromagnetic Theory*, Ph.D. dissertation, Case Western Reserve Univ., 1970; "Commitment to Mechanism : J. J. Thomson, the Early Years," *Archive for History of Exact Sciences* 7(1971), 393-410; "'To Reason by Means of Images' : J. J. Thomson and the Mechanical Picture of Nature," *Annals of Science* 37(1980), 31-57.

4) I. Falconer, "Corpuscles, Electrons and Cathode Rays : J. J. Thomson and the 'Discovery of the Electron'," *British Journal for the History of Science* 20(1987), 241-276; "J. J. Thomson's Work on Positive Rays, 1906-1914," *Historical Studies in the Physical and Biological Sciences* 18(1988), 265-310.

5) I. Falconer, op. cit. (1987), 252.

concerned with gas discharge phenomenon from his vortex-atom theory, and expected that the investigations on this phenomenon would reveal the relation between the disruption of a molecule(matter), the electric field and the ether, and consequently offer a unified explanation about electricity and matter. According to Falconer, Thomson, on the basis of his early research since 1883, could introduce the concept of discrete discharge in early 1890s and change fundamentally the understanding of gas discharge. The experimental understanding about gas discharge attained during these years was indispensable to his work on X-ray ionization and on cathode rays. She said that this early period had ended in 1896 after the discovery of X-rays, and evaluated Thomson's work in this period as a process of "feeling his way".<sup>6</sup>

However, Thomson's early work on gas discharge does not seem to have been the process of feeling his way. He had had the clear idea that gas discharge (electrical phenomena) and chemical changes were related to each other since about 1882, when he had not begun actual experiments yet. After becoming director of the Cavendish Laboratory, he had developed, elaborated and refined this idea through experiments and related theoretical speculations.

In this paper, Thomson's gas discharge work during about 20 years, from about 1882 to 1899, is divided into four periods and analyzed for each period to show in what way his idea had developed and changed. From this, it is shown that till the end of 1890s Thomson had had the consistent intention to reveal the relation between matter and electricity and that after the discovery of the 'corpuscle' in 1897 he applied this idea of 'corpuscle' mainly to ionization of matter.

Section II considers the theoretical, mathematical work which Thomson, as a fellow of Trinity College, had conducted after he had graduated Cambridge University from 1880 to 1884. Then, the period from 1885 to 1889, right after he became director of the Cavendish Laboratory is discussed in section III. Vortex theory was the basis of his research in this period. Section IV deals with the period from about 1890 to 1895, during which Thomson realized the analogy between gas discharge and electrolysis and paid attention to the connection between electrical and chemical phenomena. Finally, in section V, the period from the discovery of X-ray(1895. 11.) until 1899 is discussed. Through this paper, I would like to demonstrate that Thomson's 'discovery of the electron' in 1897 was also indebted to the idea that the fundamental connection exists between electrical and chemical phenomena.

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6) *ibid.*, 253-254.

## II. 1880-1884

J. J. Thomson was more of a 'mathematician' than an 'experimentalist' as has been generally accepted. It is true that he assisted Balfour Stewart in experimental research at Owens College, Manchester,<sup>7)</sup> but he had mainly studied mathematics from 1876, when he entered Cambridge University, till 1880 when he graduated from that university as a second Wrangler in Mathematical Tripos. Mathematical Tripos, the most famous graduation examination of Cambridge University, included not only a wide range of pure mathematical problems but also various application problems in physical sciences. In order to get higher grades in this examination, the ability to solve many mathematical problems in a given time was required; but experience or knowledge of experimental physics was not necessary. Thomson too, under the guidance of the coach, as most of Cambridge students of the days did, studied mathematics and trained himself to solve as many problems as possible in a given time.

Even after graduating from Cambridge University and becoming a fellow of Trinity College, the main topic of Thomson's research was still mathematical and theoretical. But he also began experimenting at the Cavendish Laboratory.<sup>8)</sup> For example, he tried to detect some effects predicted by Maxwell's theory that change of electric force in the dielectric would create magnetic field.<sup>9)</sup> At the suggestion of Lord Rayleigh, he observed the effect of the electrostatic capacity of induction coil, and in 1883 conducted experiments to determine the ratio of the electrostatic unit and the electromagnetic unit of charge ('v').<sup>10)</sup>

While these experiments were relatively simple ones, using several simple instruments to get accustomed to experimental skills, Thomson's mathematical and theoretical work during this period shows clearly that he was a well-trained Cambridge mathematician. In 1881 he investigated, on the basis of Maxwell's theory, what electric and magnetic effects would be produced by the motion of electrified

7) J. J. Thomson, *Recollections*, pp. 19-20.

8) *Ibid.*, p. 95; H. F. Newall et al., *A History of the Cavendish Laboratory, 1871-1910* (London: Longmans, Green & Co., 1910), p. 80.

9) J. J. Thomson, *Recollections*, p. 97.

10) These researches were published in 1881 and 1883 respectively. J. J. Thomson, "On some Electromagnetic Experiments with Open Circuits," *Philosophical Magazine* (hereafter, abbreviated as *Phil. Mag.*) 12(1881a), 47; "On the Determination of the Number of Electrostatic Units in the Electromagnetic Unit of Electricity," *Proceedings of Royal Society of London* (hereafter, abbreviated as *Proc. Roy. Soc.*) 35(1883), 346. Particularly, the experiment to determine 'v' was closely related with electromagnetic theory of light, because 'v' corresponds to the velocity of light in vacuum as predicted from Maxwell's theory. Thomson obtained the value of  $v = 2.963 \times 10^{10}$  C.G.S. unit through experiments.

bodies.<sup>11</sup> Applying Maxwell's equations to the problem of a moving charged sphere, Thomson obtained the result that the motion of an electrified sphere would produce an effect equivalent to an increase in mass. According to Maxwell's theory, a moving charged sphere should produce magnetic field. Thus movement of a charged body was accompanied with field energy, dependent on the intensity of field, which, in turn, depended on the velocity of the charged sphere. Force exerted from outside could increase the velocity of the charged body, and consequently raise the energy of magnetic field. As a result, electrified moving bodies must experience more resistance. Thomson concluded from this, that increase in mass of a charged moving sphere did not occur actually, but that it only appeared so due to the increased resistance of media. This shows Thomson's deep commitment to Maxwell's electromagnetic theory. This tendency appeared continually in his work of 1880s and 1890s.

Mathematical investigation of vortex motion, which was the subject for the prestigious Adams Prize for 1882, was another subject that appealed to Thomson in this period. Because vortex theory needed only to suppose "incompressible perfect fluid" as the constituent of universe and vortex motion of this fluid as the source of all the property of matter, Thomson considered the theory as more fundamental and straightforward than any other theory. The equations governing this motion of vortex were those of hydrodynamics, so that the problem of explaining nature would be reduced to the problem of solving certain differential equations. Thomson won the Adams Prize for the treatise containing long, rigorous mathematical analysis, which was published in the next year under the title of *A Treatise on the Motions of Vortex Rings*.<sup>12</sup>

It was in *A Treatise* that the description related to gas discharge appeared for the first time.<sup>13</sup> In this treatise Thomson had developed mathematically "the interaction of the two closed vortex in perfectly incompressible fluid," and, in the last chapter, applied that result to the chemical problems such as Boyle's law, thermal effusion,

11) J.J. Thomson, "On the Electric and Magnetic Effects Produced by the Motion of Electrified Bodies," *Phil. Mag.* 11(1881b), 229.

12) J.J. Thomson, *Recollections*, pp. 94-95.

13) For a long time, Thomson had taken interest in the phenomenon of gas discharge. He had already mentioned the experiments of Crookes and Goldstein on 'the discharge in the high vacua,' and tried to explain the cause of 'green phosphorescence' that appeared in their experiments with the Maxwell's theory in op. cit. (1881b). Thomson said that a moving charged body produced the vector-potential in the field through which it was moving. When a particle hit the glass directly, its velocity was reversed and the vector-potential changed its sign. Any change in the vector-potential produced a corresponding electromotive force, and thus the green phosphorescence was caused to appear. However, it was in *A Treatise* that he examined gaseous discharge in general and sought to find its cause.

chemical combination and dissociation, quantivalence theory and periodicity of elements. The phenomenon of electric discharge through gases was related to the problem of finding the effect that would be caused on chemical combination and dissociation if a molecule composed of two vortex-ring atoms was disturbed by external electric field, which was also discussed in the last chapter.

An attempt to explain some characteristic phenomena with vortex-atom theory was made in a treatise published in 1883.<sup>14)</sup> This treatise shows that Thomson's own research about the interaction of two vortex rings made him accept R. Clausius and Williamson's view about the chemical combination. According to their view, gas molecules were not always composed of the same atoms but changed partners continually.<sup>15)</sup> Thus, Thomson thought that "paired time" must be considerably longer than "free time" in order that mixed gas in this state might be more than a mere "mechanical mixture" of the elementary gases of which it was composed. If a molecule formed by pairing of two vortex rings was disturbed by such things as external electric field, the ratio of paired time to free time was reduced, and eventually chemical decomposition could occur by the absorbed energy of electric field. This molecule was recombined as soon as the disturbing factors were withdrawn. The energy emitted during this process will not return to the electric field, but will rather be emitted in the form of heat or light. Thomson regarded this phenomenon as electric discharge through gases.<sup>16)</sup>

We must note here that the dissociation of gas molecules by absorption of the energy of electric field must precede the electric discharge. In other words, chemical dissociation was not merely the by-product but the necessary condition of electric discharge, without which it could not occur. With this idea in mind, Thomson, further explained theoretically the variation of the electric strength of a gas as it was rarefied; the rarefaction of the gas would bring about a relative increase of free time, thus making the dissociation easier, and eventually the electric strength of the gas would be diminished; on the contrary, at a density lower than some critical point, much more "volume" of gas molecules must be decomposed, in order to use up the same amount of electric field energy, and thus much stronger electric field would be needed, which means that electric strength would be increased.

As we have seen so far, Thomson's research before he became director of the Cavendish Laboratory had been carried out largely to solve the concrete problems

14) J.J. Thomson, "On a Theory of the Electric Discharge in Gases," *Phil. Mag.* 15(1883), 427.

15) *ibid.*, 428. Whittaker said that this hypothesis had been widely accepted as the theoretical basis of electrolysis at the end of nineteenth century; E. Whittaker, *A History of the Theories of Aether and Electricity: the Classical Theories* (New York : Philosophical Library, 1951), pp. 335-336.

16) J.J. Thomson, *op. cit.* (1883), 430-431.

which Maxwell's electromagnetic theory had raised, and to explain various physical phenomena using mechanical models like vortex. The vortex theory had interested Thomson on the gaseous discharge phenomena, one of the phenomena that could be well explained with vortex theory. Meanwhile, the significance of many characteristics of gaseous discharge had been already pointed out by Maxwell in his *A Treatise on Electricity and Magnetism*.<sup>17</sup> Therefore, it was not accidental for Thomson, who had been studying within the Maxwellian tradition, to become interested in this phenomena; it is not simply because he had had interest in vortex theory. The fact that Thomson had taken electric discharge as his topic of experimental research after he was appointed as director of the Cavendish Laboratory shows this well.

### III. 1885-1889

Lord Rayleigh, second director of the Cavendish Laboratory had resigned from his directorship in the autumn of 1884, and Thomson was appointed as his successor in December. That decision looked extraordinary, even to Thomson himself, because he was then very young and had little career as an experimenter. He had not given a course on practical physics and never taught a laboratory class.<sup>18</sup> The Cambridge men, however, judged Thomson to have enough scientific talent and potential to lead the Cavendish Laboratory successfully and chose him as a successor to Maxwell and Lord Rayleigh.<sup>19</sup>

Thomson's appointment as director of the Cavendish Laboratory brought about a significant change to his research activity. As indicated in the previous section, up to 1884 Thomson's research had been theoretical and mathematical rather than experimental. But now his new position as professor of experimental physics and director of the Cavendish Laboratory conditioned and motivated him to carry out experimental research. Such a change was revealed best in his research on gaseous discharge. Thomson's previous research on this subject had been carried out largely

17) "These, and many other phenomena of electrical discharge, are exceedingly important, and when they are better understood they will probably throw great light on the nature of electricity as well as the nature of gases and of the medium pervading space." J.C. Maxwell, *A Treatise on Electricity and Magnetism* (New York : Dover, 1954), vol. 1, p. 61.

18) J.J. Thomson, *Recollections*, pp. 97-98.

19) D.W. Kim, *The Emergence of the Cavendish School: An Early History of the Cavendish Laboratory, 1871-1900*, Ph.D. dissertation, Havard University, 1991, especially pp.116-131. Kim argues that, in addition to Thomson's scientific talent, preference for the Cambridge graduate, and the fact that Thomson had been experimenting at the Cavendish Laboratory during the previous five years, had acted to the advantage of Thomson.

to provide theoretical interpretation of the experimental results of others, while, after becoming director, Thomson began to experiment by his own hands with the help of R. Threlfall etc.

Thomson at first observed what chemical changes would occur in gases like nitrogen and oxygen, when traversed by the electric discharge. When he sent the electric discharge through nitrogen gas under a low pressure below 20mm Hg for enough time, the volume of the gas diminished.<sup>20)</sup> The diminution in volume continued until it reached a maximum. At a pressure of 16mm Hg, 2-3% of the original volume could be reduced, while at 8mm Hg 8-12% was diminished. These maximum values were obtained after Thomson had continuously passed sparks of 4 inches through the discharge tube of 1 cm diameter and 25 cm long for 8 hours. The reduction ratio was independent of the volume of discharge tube and the area of its surface, and the material constituting electrodes made little, if any, difference on the ratio, either.<sup>21)</sup> He considered this change as analogous to the transformation of oxygen into its allotrope ozone, and explained that the allotropic modification of nitrogen gas by sparks caused the volume to diminish. Sparked nitrogen gas, when heated to about 100°C for an adequate period of time, regains its lost volume, just as ozone comes back to oxygen when heated, and Thomson regarded this phenomena as a process of recovering from allotropic modification.

Is it necessary, then, to pass sparks through the gas in order to modify a gas into its allotrope? In 1886 Thomson sought to answer this question through experiments on the production of ozone.<sup>22)</sup> He made a box with one surface made of glass so that electric discharge might be perceived when traversed. Two glass tubes were inserted into this box so that the air might enter the box through one of the two tubes and leave it through the other after circulating in the box. The air, after passing through the box, was made to pass through a test-tube, containing an iodide of potassium (KI) and starch solution; the coloration of this solution would mean the production of ozone. With blackened tin plate and water containing a little sulphuric acid as two electrodes, Thomson could apply electric field to the gas passing through the box, and by varying the interval between the electrodes he could control the intensity of electric field. When the field was not intense enough to produce a spark, Thomson could not detect the slightest coloration in the test-tube even after passing for more than an hour. Passage of a single spark,

20) J.J. Thomson & R. Threlfall, "On an Effect Produced by the Passage of an Electrical Discharge through Pure Nitrogen," *Proc. Roy. Soc.* 4(1886a), 329-340.

21) Thomson used two electrodes made of aluminum and plutonium respectively, and attained the same results for each case. *ibid.*, 330.

22) J.J. Thomson & R. Threlfall, "Some Experiments on the Production of Ozone," *Proc. Roy. Soc.* 40(1886b), 340-342.

however, was sufficient to produce a distinct coloration. From these results, Thomson concluded that however strong an electric field was applied to the oxygen, ozone was not produced unless sparked.

Next, Thomson investigated the appearance of the electric discharge in a uniform electric field, and experimented to see what changes would be made in a gas when its pressure was reduced.<sup>23</sup> Unlike the discharge experiments mentioned above, those in a uniform electric field had the advantage that the state of the field could be accurately known before the discharge took place, which especially attracted Thomson's attention. He arranged two parallel plates to be separated by a distance very small in comparison with their diameters, and made the curved parts of the plates smooth, which was to weaken the non-uniform field effect arising at the edge of the plate as much as possible, and thus to make the electric field between two plates as uniform as can be. Some characteristics appeared as sparks were sent through between two parallel plates and the pressure gradually diminished. Most remarkable was that what happened at positive and negative electrode were different from each other. The discharge in the shape of a disc emerged at negative electrode when the pressure sank below 90mm Hg. And as the pressure diminished the disc near negative electrode broadened out, while the discharge at positive electrode and between two electrodes got smaller. The color of the discharge kept changing until it became very distinct, bluish at negative electrode and reddish at positive electrode. When the pressure reached 4mm Hg, this disc appeared to constitute the whole of the discharge. As the pressure further diminished, the disc gradually moved away from negative electrode, and the color of the discharge kept changing to become "pale Cambridgian blue". When an air-break was put in the circuit, a glow was distinctly visible above the upper negative electrode. When tried with electrically very weak gases such as the vapors of turpentine and alcohol, the discharge was not confined to a disc near negative electrode but stretched across the space between the electrodes, even though the disc was still brighter than the rest.

Thomson, according to his vortex theory, explained the difference between the effect observed at positive and that at negative electrode as follows.<sup>24</sup> A molecule

23) J.J. Thomson, "On some Experiments on the Electric Discharge in a Uniform Electric Field, with some Theoretical Considerations about the Passage of Electricity through Gases," *Proceedings of Cambridge Philosophical Society* (hereafter, abbreviated as *Proc. Camb. Phil. Soc.*) 5 (1886c), 391-409.

24) Maxwell had mentioned the significance of this phenomena in his *Treatise*, therefore it seemed to be natural that Thomson, who had been studying within the Maxwellian tradition, became interested in this phenomena: "This and many other differences between positive and negative electrification must be studied by those who desire to discover something about the nature of electricity," J.C. Maxwell, *A Treatise*, p. 60.

composed of two vortex rings would tend to separate when it was moving in one direction in an electric field, but would be pushed nearer together when the molecule was moving in the opposite direction. If we suppose the former to be the direction toward negative electrode and the latter to be the opposite direction, it followed that at negative electrode those molecules moving toward it had tendency to be decomposed, while at positive electrode molecules moving away from it had the same tendency. Consequently, the molecules would be more easily decomposed at negative electrode than at positive electrode and in the rest of the gas, which explained the fact that sparks passed more easily from negative to positive electrode than in the opposite direction.<sup>25</sup>

Many direct evidences seemed to support such a view of Thomson. In the first place, it was known that the glow of a gas surrounding negative electrode in vacuum tube generally showed a line spectrum, while a band spectrum tended to appear at the rest of vacuum tube. Line spectra were believed to denote a simpler molecular constitution than band spectra, and thus this could be an evidence that a considerable amount of decomposition was going on near negative electrode. Secondly, the fact that the gas near negative electrode was hotter than that in the rest was another supporting evidence.<sup>26</sup>

Another important consequence derived from Thomson's vortex theory was that molecules of a gas should be dissociated in order to pass discharge through it. Thus the decomposition of gas molecules ought to be observed when the gas was traversed by the discharge. Thomson conducted some experiments in order to confirm this, and announced the results in the Bakerian Lecture of the Royal Society for 1887. He sent electricity through such gases as iodine, bromine, chlorine, and nitrogen tetroxide, and recorded the consequent variation of the pressure and the vapor-density.<sup>27</sup> Thomson placed iodine vapor inside a tube with a conduction coil and gave sparks about 3 inches long in air. The pressure rapidly increased at first, but the rate of increase gradually diminished and the pressure reached a steady state. Even after stopping the coil, increased pressure lasted for several hours at least. This increase of pressure could be produced by the "silent discharge" as well as by ordinary sparking.<sup>28</sup> Thomson believed this increase to result from the

25) This fact had been observed by Faraday: M. Faraday, *Experimental Researches in Electricity* (New York: Dover, 1839-1855) vol. 2, # 1501.

26) J. J. Thomson, op. cit. (1886c, see footnote 23), 399-400.

27) J. J. Thomson, "On the Dissociation of some Gases by the Electric Discharge," *Proc. Roy. Soc.* 42(1887), 343-345.

28) It was a form of electric discharge in which the thermal effects were as small as possible, and it could be produced by using Siemens' ozonizer. The outline of Siemens' ozonizer was represented in J. J. Thomson, *Notes on Recent Researches in Electricity and Magnetism* (Oxford:

dissociation of considerable amount of iodine vapor. In the case of bromine too, even though the atoms recombined as soon as they sparked and the pressure recovered, the molecules were certainly decomposed.

Clearly, Thomson, with the vortex theory as the basis of his argument, had affirmed the importance of the decomposition in the electric discharge. What he considered essential for the electric discharge, however, was that "there should be some means of 'dissipating' the energy of the electric field"<sup>29</sup> rather than the 'decomposition' itself. The decomposition was regarded as only one way of dissipating. Such view was revealed more clearly in the explanation of Arthur Schuster's experiment on the electric discharge through mercury vapor.<sup>30</sup> Mercury vapor was monatomic, thus it could not be dissociated. The experiments of Schuster, however, showed that the discharge still occurred in mercury, even though with quite different characteristics. Therefore, there must be some means of dissipating the energy of the electric field other than that of the decomposition of molecules. Thomson believed the "other means" to be 'radiation', on account of the luminosity, one of the striking features of the discharge phenomena. Radiation was affected not by external forces but only by temperature, and thus energy loss each time was slight. However, when the applied electric field was so intense as to make molecules to have considerably high velocity in the intervals between each collision, it was believed that the field energy sufficient to produce sparks could be dissipated.

In addition, in 1889 Thomson investigated the effect of pressure and temperature on the decomposition of gas molecules, i.e. on the changes in the electric strength of the gas, particularly of carbonic acid.<sup>31</sup> The electric strength of CO<sub>2</sub> increased with pressure and this increase went on beyond the point of liquefaction: the strength of liquid CO<sub>2</sub> was greater than that of gaseous CO<sub>2</sub> just before the liquefaction. On the other hand, the electric strength of highly condensed CO<sub>2</sub> increased in proportion to temperature. But further investigation showed Thomson that the electric strength of a gas was dependent not on temperature but on density, the number of molecules in unit volume.

To sum up, Thomson's researches on electric discharge through gases conducted during this period was to confirm experimentally several consequences of the vortex

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Clarendon Press, 1893), p. 178.

29) J.J. Thomson, op. cit. (1886c, see footnote 23), 407. According to Falconer, Thomson was still within the tradition of Maxwellian electromagnetism, and the Maxwellian tradition viewed electricity as a strained state of the ether. Discharge was a relaxation of this strained state, with the subsequent dissipation of energy. I. Falconer, op. cit. (1987, see footnote 4), 260.

30) J.J. Thomson, op. cit. (1886c), 407.

31) J.J. Thomson, "On the Effect of Pressure and Temperature on the Electric Strength of Gases," *Proc. Camb. Phil. Soc.* 6(1889), 325-328.

theory, and to find out the details of the phenomena of electric discharge. He also often attempted to explain the phenomena with the vortex theory, at least in part.

Nevertheless, Thomson's major concern during this period was still focused on the research of electromagnetism. In fact, among the twenty-two articles he published from 1885 to 1889, only five dealt with the phenomena of electric discharge directly. During this period, as during the previous one, Thomson continually tried to solve several specific problems arising from Maxwell's theory through simple experiments. For instance, he investigated, according to Maxwell's theory, the electrical oscillation on cylindrical conductors and compared this result with those of Helmholtz's and Kirchhoff's theories.<sup>32</sup> He demonstrated mathematically that the velocity of very rapidly alternating currents passing through conductors should be equal to the rate of propagation of electromagnetic action, as predicted from Maxwell's theory,<sup>33</sup> and attempted to harmonize this result with the discovery of Hertz that 'the velocity of propagation along a wire was smaller than that of currents.'<sup>34</sup> Measuring a specific inductive capacity of dielectrics was also an important task to prove the adequacy of Maxwell's theory.<sup>35</sup>

Another subject in which Thomson became interested after he assumed the directorship of the Cavendish Laboratory was the phenomena of electrolysis. Its analogy with the mechanism of gaseous discharge attracted Thomson's attention. But it was not until 1890s that these two researches became related to each other and the theory of electrolysis was used to explain the phenomena of gaseous discharge.

#### IV. 1890-1895

In addition to gas discharge, electrolysis was another major subject of the research carried out at the Cavendish Laboratory during the same period. Electrolysis refers to the phenomenon that a part of electrolyte is chemically decomposed

32) J.J. Thomson, op. cit. (1886c, see footnote 23), 391; "Electrical Oscillation on Cylindrical Conductors," *Proceedings of London Mathematical Society* 19(1888), 520.

33) J.J. Thomson, "The Resistance of Electrolytes to the Passage of Very Rapidly Alternating Currents, with some Investigations on the Times of Vibration of Electrical Systems," *Proc. Roy. Soc.* 45(1889), 269-290.

34) J.J. Thomson, "Note on the Effect Produced by Conductors in the Neighbourhood of a Wire on the Rate of Propagation of Electrical Disturbances along it, with a Determination of This Rate," *Proc. Roy. Soc.* 46(1889), 1.

35) J.J. Thomson, "Specific Inductive Capacity of Dielectrics when Acted on by Very Rapidly Alternating Electric Forces," *Proc. Roy. Soc.* 46(1889), 292.

by the current, and ions, the products of the decomposition, are deposited at the electrodes. The current acts on the molecules constituting the liquid electrolyte to decompose them into two ions, each of which is charged with different electricities. That is to say, "there is no conduction without chemical decomposition." According to the Faraday's law of the electrolysis, which was generally accepted among researchers at the time, "the weight of the electrolyte decomposed is proportional to the quantity of electricity transmitted," and "the same quantity of electricity produces in different electrolytes the separation of chemically equivalent amounts of ions."<sup>36</sup>

The phenomena of electrolysis attracted the attention of many physicists as well as the researchers working at the Cavendish Laboratory. As early as in 1882, Wiedemann had compiled the facts and theories related to electrolysis and electrochemistry announced by the end of the year. H. von Helmholtz, too, in his Faraday Lecture for 1881, had pointed out the importance of this subject. As interest in the phenomena increased, the British Association for the Advancement of Science appointed a committee "for the purpose of considering the subject of electrolysis in its physical and chemical bearings" in 1885. With Oliver Lodge and Armstrong as secretaries, the committee had William Thomson, Lord Rayleigh, Arthur Schuster, J.H. Poynting, J.J. Thomson, W.N. Shaw, W. Crookes, and J. Larmor as its members. They communicated with each other by correspondence, and individually undertook the investigation of various points more or less closely bearing on the subject, some of which were edited by Lodge and published in the annual report of the British Association.<sup>37</sup>

Thomson, as one of its members, worked at the Cavendish Laboratory with H.F. Newall on the electric conduction through bad conductors such as benzen, olive oil, paraffin oil and carbon bisulphide.<sup>38</sup> The question with which they were concerned was whether these materials would follow Ohm's law, which was the second question suggested by Lodge for the committee to investigate. Quincke had already answered this question by finding that, when the electromotive force was large enough to cause a spark to pass through a liquid, Ohm's law did not hold even approximately. Thomson and Newall, however, demonstrated experimentally that even in the electromagnetic force of up to 100 volts these bad conductors obeyed

36) Shaw's report printed in the BA report for 1890 summarized well the current discussion about electrolysis. W.N. Shaw, "Report on the present state of our knowledge in electrolysis and electro-chemistry," *BA Report-1890*, 185-223.

37) *BA-report for 1886*, 308-9.

38) The result of their research was published independently. J.J. Thomson & H.F. Newall, "On the Rate at which Electricity Leaks through Liquids which are Bad Conductors of Electricity," *Proc. Roy. Soc.* 42(1887), 410-429.

Ohm's law very well. They also found that conductivity increased with temperature.<sup>39)</sup>

In the meantime, the remarkable analogy between electrolysis and gas discharge began to arrest Thomson's attention, especially in the 1890s. He had already mentioned in a paper published in 1886, that "according to our view, the process in both cases is very much the same,"<sup>40)</sup> and later works by Helmholtz and others supported Thomson's view more strongly. Helmholtz, in collaboration with Richarz, found that electric discharge and chemical combination produced dense condensation in the steam-jet in the neighborhood.<sup>41)</sup> Heretofore, the close relation between electrical and chemical phenomena had been regarded as a characteristic of electrolysis, but Helmholtz's experiments showed that gaseous discharge had the same feature as electrolysis. As Thomson himself had indicated, ever since Faraday discovered the law of electrolysis, many scientists had been trying to examine closely the connection between electrical and chemical phenomena through experiments on electrolysis.<sup>42)</sup> Now Thomson realized that study on gas discharge phenomena, no less than work on electrolysis phenomena, could solve the problem of the connection between chemical and electrical phenomena, and, more fundamentally, the question of the relation between matter and electricity. Moreover, the gaseous state had been studied most closely, because its chemical properties are the simplest and it is easy to see what is going on inside. This made the study of discharge as more adequate means than any other to study chemical problems of matter.

Thomson believed that the 'decomposition' of molecules of the medium was essential for electricity to pass through liquid electrolyte or gas, and for the electric discharge to occur. The electrolysis had been generally explained as a process in which the current passing through an electrolyte makes the molecules of the electrolyte to be decomposed, and the electricity is conducted through the migration of ions thus produced. Such mode of explanation regarding 'dissociation' as an essential factor of the electric conduction was consistent with Thomson's explanation of gas discharge based on the vortex theory. Previously, Thomson had remarked from the vortex theory that it was essential to dissipate the energy of electric field by decomposing of molecules. What Thomson considered more important at that time, however, was instant 'dissipation' of molecules. But when he came across

39) *BA Report-1886*, 318-328.

40) J. J. Thomson, op. cit. (1886c, see footnote 23), 403.

41) R. v. Helmholtz, *Wiedemann's Annalen der Physik und Chemie* (hereafter, *Wied. Ann.*) 32 (1887).

1; R. v. Helmholtz and Richarz, *Wied. Ann.*, 40 (1890), p. 161, which was quoted in "On the Effect of Electrification and Chemical Action on a Steam-jet, and of Water-Vapour on the Discharge of Electricity through Gases," *Phil. Mag.* 36 (1893), 318.

42) J. J. Thomson, "The Connection between Chemical Combination and the Discharge of Electricity through Gases," *BA Report-1894*, 482.

the theory of electrolysis, he appreciated the significance of 'decomposition' and thus came to consider decomposition more fundamental than the dissipation of field energy.

Such change of his thought was reflected on the fact that Thomson, in 1890's, was interested in the transmission of electricity through hot gases.<sup>43</sup> As he came to pay attention to 'dissociation' of molecules, he could think about, as means of making dissociation other than applying the electric field, heating up the gas to raise its temperature.<sup>44</sup> Thomson was able to confirm the dissociation by heating "by purely chemical means." For instance, potassium iodide, when heated, was made to pass rapidly through the starch solution, so that if the molecules were dissociated, the color of the starch solution would be changed into blue by the presence of iodide atoms. The presence of iodide atoms was detected by the coloration of the starch solution. In the case of the hydrochloric acid gas, too, Thomson observed the coloration of the solution.<sup>45</sup>

When molecules were split in this manner, the electric conductivities of gases increased. However, the conductivities of all the gases did not increase to the same degree. Such gases as hydrochloric acid, hydriodic acid, potassium iodide, sodium chloride, iodine, and bromine attained very high conductivity when heated, while in the case of ammonia, water vapor, air, nitrogen, mercury vapor, their conductivities increased only slightly. Thomson explained this difference as follows: in the former case, atoms were produced from the splitting of molecules, while, in the latter case, molecules were merely splitted into simpler molecules. In the first type of dissociation, the atoms produced, which were charged with electricity, made the conduction possible, while, in the second type, molecules, which were electrically neutral, were unable to transmit electricity. High conductivity of metals also supported Thomson's view, for metal was believed to be monatomic, and thus, metal itself, without dissociation, could conduct electricity.

The hypothesis that charged atoms were responsible for the electric conduction,

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43) J.J. Thomson, "On the Passage of Electricity through Hot Gases," *Phil. Mag.* 29(1890), 358.

44) This fact was contrasted with the previous interpretation that, in order to discharge mercury molecules which were monatomic, there must be other means than the dissociation to 'dissipate' the energy of the electric field. Thomson, at that time, had considered the dissipation of energy as essential to the electric discharge, thus radiation was believed to be one of the other means. On the contrary, now Thomson regarded 'the dissipation of the field energy' as essential, so he could think about applying the electric field and raising temperature as means to dissociate the molecules.

45) In the case of hydrochloric acid gas Thomson used the mixture of a starch solution and iodide of potassium instead of the solution of starch alone. When free chlorine atoms dissociated from the HCl were made to bubble through the solution, free chlorine set free iodine from the potassium iodide and produced a blue coloration of the solution.

however, had two problems. First, if atoms retained the same quantity of electricity as that of ions in the conduction through liquid electrolyte, the electrical attraction between atoms in the molecule would be too great to split a molecule with the electric field given in the laboratory. Second, the velocity with which charged atoms could migrate through the gas was far less than the velocity of the discharge, which approached that of light. Supposing an atom itself conducted electricity, migrating with the velocity of light, the kinetic energy of the atom was calculated to be enormously greater than the potential which was obtained in the laboratory.<sup>46</sup> Thus in order to dissociate a molecule into atoms, which are the carriers of charge, electric attraction between atoms must be weakened first with some methods. And if the discharge occurred by the free atom, it was clear that it could not occur through the actual migration of atoms.

While trying to solve these problems, Thomson proposed a new mechanism of chemical changes of the gas medium when sparked. The mechanism previously advanced by Thomson was that, in accordance with the vortex theory, the electric field when applied to a gas produced disturbance in a gas molecule and split the molecule into two vortex-ring atoms. In contrast, the new one presupposed formation of chains of molecules in gas discharge, which were analogous to the Grotthus chains in electrolysis. As the intensity of the electric field increased up to the point not high enough to cause discharge, the induction in the field polarized the gas molecules. Such polarized molecules joined together to form aggregates of molecules similar to those in electrolysis, and then the electrical attraction inside the aggregates was weakened by adjacent atoms. Thomson believed atoms are separated from aggregates more easily than from a single molecule. If it was supposed that a series of chains had been already formed in the path of the discharge and atoms of each molecule constituting chains were decomposed from their partners and recombined with others in the opposite side simultaneously, Thomson, by properly choosing the length of the chain, could explain the propagation of discharge at a velocity which is near that of light. Stratification, one of the remarkable features of discharge, Thomson thought, was the evidence that such chains really existed.<sup>47</sup>

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46) In the case of a parallel-plate condenser separated by 1cm, the amount of kinetic energy of an atom was calculated to be 8000 times the electric field energy. "Some Experiments on the Velocity of Transmission of Electric Disturbances, and their Application to the Theory of the Striated Discharge through Gases," *Phil. Mag.* 30(1890), 129-140, see especially pp. 131-133; J. J. Thomson, "On the Rate of Propagation of the Luminous Discharge of Electricity through a Rarefied Gases," *Proc. Roy. Soc.* 49(1891), 84-100, see especially pp. 92-93. With accurate experiment, Thomson could confirm that the propagating velocity of the positive column approached that of light.

47) J. J. Thomson, *Recent Researches*, p. 192-8; op. cit. (1890), 132-3; op. cit. (1891), 92-4.

On the other hand, if it was true that the gaseous discharge was accompanied by the same sort of chemical change as those in the electrolysis, it was natural to reason that the charge-carrying atom thus produced should carry the electricity of the same sign as that of the electrolyte. Such view of Thomson seemed to be supported by the experiments of Perrot.<sup>48</sup> Perrot had connected a discharge tube, with steam in it, in series with a voltmeter, and sent discharge through it. He found that in the case of electrolysis of steam, as in that of water, the excess of hydrogen appeared at the negative electrode, the excess of oxygen at the positive, and these excesses were very nearly chemically equivalent to the amount of copper (Cu) deposited in the voltmeter.

When Thomson himself repeated the experiment of Perrot, with varying lengths of sparks, however, he did not obtain the same results. The amounts of oxygen and hydrogen were nearly the same as those liberated at the water voltmeter placed in series with the discharge tube, but according to the length of sparks the electrodes at which each gas was produced were different. With the 11-22mm long sparks, oxygen appeared at the positive electrode and hydrogen at the negative; but when the sparks were shorter than this, that is, for the arc discharge, the results were reversed.<sup>49</sup> For all these differences, Thomson concluded that "in the electrolysis of steam, as in that of water there is a very close connection between the amounts of hydrogen and oxygen liberated at the electrodes and the quantity of electricity which passed through the steam", "and that "this relation for certain lengths of sparks is the same in steam as in electrolytes."<sup>50</sup>

But the peculiar result that hydrogen and oxygen, contrary to the commonly received views of electrochemical properties of these gases, came off at the positive and negative electrodes respectively, caught Thomson's attention. With the object of elucidating this peculiarity, Thomson made a series of experiments, and in doing so he came to feel certain that the research on gaseous discharge could reveal the relation between matter and electricity, and further the connection between the chemical reaction and the discharge phenomena. After the experiments on arc discharge, Thomson's work on gas discharge proceeded to discover the mechanism of chemical combination through the experiments on electric discharge, and then the mechanism of electric discharge through gases.<sup>51</sup>

Thomson first placed the electrode into various gases where the arc discharge was occurring, and he found that the electrode was charged with positive electricity in

48) Brief explanation about the experiment of Perrot was found in J. J. Thomson, *Recent Researches*, pp. 182-184.

49) J. J. Thomson, "The electrolysis of steam," *Proc. Roy. Soc.* 53(1893), 90-110.

50) *ibid.*, 104.

51) *ibid.*, 105-108.

the oxygen gas, with negative in the hydrogen. Moreover, when he put the negatively charged electrode in the oxygen gas, it lost its charge very rapidly and acquired a positive charge. On the contrary, the positively charged electrode in the hydrogen gas got a negative charge. He sought to see if this charging up of the electrodes was due to the electricity transferring to the electrode from the gas by the contact between them, or whether it was due to an electrostatic induction by the charge on the gas. For this, he covered the electrode with a non-conductor and repeated the same procedure. If the electrification was due to the contact of the gas with the electrode, it must disappear when the electrode was covered with a layer of a non-conductor; if, however, it was due to the electrostatic induction, the electrode would be charged. Thomson found that the same result was attained, whether it was covered or not, which showed that the hydrogen and oxygen gases did not carry real charges of negative and positive electricity respectively.

As to the results of these experiments, Thomson explained that when an electric discharge passed through a gas the chemical properties of the gas in the neighbourhood of the line of discharge were modified. More specifically, if relatively long sparks were sent through a gas, the gas earned the time to recover from its chemical modification before the next sparks arrived. If, however, sparks were short like those of arc discharge, the gas could not have enough time to return to its original condition. In other words, the hydrogen and oxygen behaved as if they carried negative and positive charge respectively, though their real charges were the opposite, because the chemical properties had been changed by the sparks. Thomson thought the modification and recovery of the properties of gas was due to the continuous dissociation and combination of the gas molecules just as it was in the conduction of electricity through electrolyte.<sup>52)</sup>

With the preceding facts in mind, Thomson expected that the experiments on gas discharge would reveal some characteristics of the relation between the discharge phenomena and the chemical reaction. It was also certain that such investigation would reveal the state of the substance when it is conducting electricity, and the state of gaseous substance when participating in chemical combination. Thomson, thereafter, pursued the potential that arc discharge seemed to promise.<sup>53)</sup>

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52) *ibid.*, 108-9.

53) *ibid.*, 105; Stuart M. Feffer also understood this experiment in the same context. Feffer, comparing Thomson's gas discharge experiments with those of Schuster, said that while Schuster's intention was to show that Faraday's law was verified also in the gas, Thomson, more comprehensively, intended to explain electric discharge electromagnetically, that is, with an interaction between field and atoms. Feffer believed that Thomson found out, through experiments on arc discharge, the vital clue to the electromagnetic explanation of chemical combination. Stuart M. Feffer, "Arthur Schuster, J.J. Thomson, and the Discovery of the

In fact, there were many instances which showed the intimate analogy between electric discharge through gases and chemical combination. Thomson, in 1894, focused his attention on the fact that water vapor had the same effect both on the electric discharge and on the chemical combination.<sup>54)</sup> It had already been known, by the researchers such as Dixon, Pringsheim, and Baker, that water vapor not only gives a great effect on the chemical combination, but also is indispensable for several chemical combinations, without which chemical reaction could never occur. Take hydrogen and chloride for instance, even in those gases which had large chemical affinities, chemical combination did not occur in completely dry state, but the addition of a little water vapor was sufficient to cause a vehement chemical combination. Another effect of the aqueous vapor was on the potential difference which was required to initiate sparks. Thomson showed experimentally that, in dry gas, a much larger potential difference was required than was necessary to get the same effect in damp gas.<sup>55)</sup> The fact that water vapor exerted the same effect both on the chemical action and on gaseous discharge, Thomson thought, demonstrated the intimate analogy between two phenomena.<sup>56)</sup>

If the first discharge through a gas in its normal state was accompanied by the splitting up of some of molecules of the gas, then it was natural to believe that a cause which facilitated the first discharge should also increase the tendency of the gas to enter into the chemical combination. And once a discharge passed through a gas, dry or wet, the changes produced on the media would certainly render the next discharge easier to pass. Such view was confirmed to be true by experiments. Thomson thought that the potential difference required to produce an electric discharge was the work which was necessary to bring out chemical change, that is, to split up the molecules of the gas into atoms.

Thomson intended to go further from this, with the experiments on gas discharge, to show the mechanism of chemical combination. He attempted, in 1895, through the experiment on electrolysis, to determine the signs of the electrical charges carried by atoms in a molecule of a compound, and expected that from those works he could infer in what way the chemical combination would occur.<sup>57)</sup> For this purpose, he first sent the electric discharge through a gas to decompose the molecules of the gas, and then observed the movement of ions by the spectroscope.

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Electron," *Historical Studies in the Physical and Biological Science* 20(1989), 33-61, see especially p. 53.

54) J.J. Thomson, op. cit. (1894, see footnote 42), 483-5.

55) *ibid.*, 484.

56) Through the gas such as iodine, the discharge occurred more easily when heated, and such fact indicated the connection between two phenomena. *ibid.*, 488.

57) J.J. Thomson, "On the Electrolysis of Gases," *Proc. Roy. Soc.* 58(1895), 244-257.

The experimental procedure consisted of sending the discharge through a tube so arranged that the spectra close to positive and negative electrodes could be observed, and detecting ions deposited on each electrode from the spectra.<sup>58</sup>

The signs of the charges carried by atoms thus produced was not always constant. Because the charges of atoms produced in the electrolysis of solutions had been thought to have a constant sign, it was a striking phenomenon. For instance, the chlorine atom, when produced by the electrolysis of hydrochloric acid (HCl), was observed mostly at the positive electrode; while, the spectral lines of chlorine splitted from sulfur chloride (SCl) were brighter at the negative than at the positive electrode.<sup>59</sup> That the same atom might carry the charges of different signs according to its partner enabled Thomson to explain the chemical combination such as the reaction  $H^+H^- + Cl^+Cl^- = 2HCl$ . In this case, in order for a hydrogen atom and a chlorine atom to combine and to form a molecule of hydrochloride, an interchange of electric charges between the atoms had to precede. The variability of the sign of the charge carried by atoms meant that such interchange could really occur. Thomson distinguished between two classes of chemical reaction; one was those which should require an interchange of electric charges between atoms; the other was those which did not necessarily require any interchange of electricity and had only to rearrange the atoms as in the reaction  $CH_4 + Cl_2 = CH_3Cl + HCl$ . With the concept of the volta potential which he had introduced in *Recent Researches in Electricity and Magnetism* in 1893, Thomson explained the affinity of each atom for a certain charge, and thus the interchange of electricity between atoms. Volta potential had something to do with the nature of an atom, and the difference of potential between two metals A and B, when placed in contact, could be expressed by the difference of volta potential.<sup>60</sup> To take hydrogen and chlorine as a concrete example, prior to combination, half the hydrogen atoms had negative charges, and half the chlorine atoms got positive ones. Thus an interchange of electricity between hydrogen atoms carrying negative charge and chlorine atoms of positive charge must precede the formation of molecules of hydrochloride. When the charges were interchanged, the potential energy would diminish by the amount of twice the difference of the volta potential between two atoms. On the other hand, by separating the negative charge from the hydrogen atom and moving it close to the negative charge on the chlorine atom, the potential energy would increase by the amount of the potential difference

58) *ibid.*, 244.

59) *ibid.*, 249-250. But the sign of the electricity carried by each atom was not completely arbitrary. As shown from a zinc which attracted a positive charge more strongly than a negative charge, some definite affinity existed.

60) J. J. Thomson, "The Relation between the Atom and the Charge of Electricity Carried by it," *Phil. Mag.* 40(1895), 520-537.

between atoms in a molecule. If the former energy exceeded the latter one, Thomson thought, the interchange would occur.

Meanwhile, the experiments by J.B. Peace at the Cavendish Laboratory showed that "the potential difference between the atoms in a molecule placed so as to be free from the action of other molecule was of the order of the minimum potential difference required to produce a spark."<sup>61</sup> For several gases, it was possible to estimate directly the work required to split up a molecule into atoms. E. Wiedemann and Ludwig Boltzmann had measured the work required to decompose a hydrogen molecule and a iodine molecule respectively, and the potential difference indicated by them far exceeded the difference of volta potential. Because an isolated molecule had very small volta potential like this, there had to be some means of lowering the potential difference between atoms in a molecule for the chemical combination to occur. One method was to form a physical aggregation of molecules prior to the chemical combination. Some substance having a large specific inductive capacity would help the formation of these aggregates.<sup>62</sup> Thus, chemical reaction was thought by Thomson to take place not between a single pair of molecules, but between aggregates of molecules which had been formed prior to the chemical combination. For example, when hydrogen and chlorine molecules were combined to produce hydrochloride molecules, physical aggregations of hydrogen molecules and chlorine molecules was formed first; next, the charges of electricity were interchanged between  $\text{Cl}^+$  and  $\text{H}^-$  in the aggregates; then, the aggregates of  $\text{HCl}$  molecules were formed; and finally this aggregates would be broken up into individual molecules of  $\text{HCl}$ .

Such mechanism of chemical combination offered important suggestions about the mechanism of electric discharge through gases. In particular, the aggregates, which Thomson had considered a general state of matter, and the double coating of electricity, the existence of which Lenard had hypothesized in order to explain the peculiar electric effect produced by falling drops, were very suggestive about the state of gases when traversed by a discharge. Thomson, by observing some phenomena when an electric discharge was passing through an exhausted tube, came down to the conclusion that bodies were covered with this double coating of electricity. He showed that the signs of charges carried by water drops and the air around them were variable according to the gas, its kind and properties.<sup>63</sup> The

61) J.B. Peace, "On the Potential Difference Required to Produce a Spark between Two Parallel Plates in Air at Different Pressures," *Proc. Roy. Soc.* 52(1892):recited from *ibid.*, 525.

62) Thomson had already suggested that aggregates of gas molecules should be formed prior to the electric discharge. As the research on the discharge advanced, the aggregates proved to be very universal state of matter.

63) J.J. Thomson, "On the Electricity of Drops," *Phil. Mag.* 37(1894), 341-358.

state of matter on the surface of a water drop was intermediate between a complete chemical combination and a complete separation between the gas and the liquid forming the drop, and when the drop of liquid fell on a plate, the incomplete compound would be split up, and electrify itself and the surrounding air. This state of incomplete chemical combination, which Thomson regarded as an "attempt" or "tendency" towards chemical combination, was a very common phenomenon at ordinary temperature.<sup>64)</sup> If such process of chemical combination stopped at the stage of the interchange of charges between atoms, and if one of the substances participating in the combination was solid or liquid, while the other was gas, then it was thought that two layers of electricity would exist between these two substances.

Water was typical of the substances which, forming incomplete chemical combination, exerted electrical effects on the surroundings. Water could put the surrounding gas, more easily than any other, into a condition where the atoms were loosely attached together, which facilitated the discharge.<sup>65)</sup> When the water drop evaporated, only the atoms, forming a double layer of electricity, that is, the atoms of the opposite charges loosely connected, would be left behind and attract the surrounding substances as a nucleus to form the aggregates. The aggregates thus produced was considered to be split easily and conduct the electric discharge.

Thomson regarded it important to investigate, in this manner, the connection between matter and the charge carried by atoms,

The connexion between ordinary matter and the electrical charges on the atom is evidently a matter of fundamental importance, and one which must be closely related to a good many of the most important chemical as well as electrical phenomena. In fact a complete explanation of this connexion would probably go a long way towards establishing a theory of the constitution of matter as well as of the mechanism of the electric field.<sup>66)</sup>

He emphasized the connection between electrical and chemical effects, because he believed that this connection would throw light on the mechanism of gas discharge and that of chemical combination of matter, and more fundamentally the relation between matter and electricity.

As has been shown above, Thomson had consistently pursued the subject of the connection between electricity and matter through 1880s and 1890s. Since early

64) J.J. Thomson, op. cit. (1895, see footnote 58), 528-529.

65) With the exception of mercury, water was the substance showing the electrification by the drops most strongly. *BA Report-1894*, 486-487.

66) J.J. Thomson, op. cit. (1895, see footnote 60), 512.

1890s, in particular, when he had recognized the prominence of the gas discharge experiment as a tool for the investigation of this problem, Thomson's researches on the electromagnetism were centered on the gas discharge. As indicated in the previous section, it was not until 1890 that the phenomena of electric discharge had occupied the central position in his study on the electromagnetism. More important to Thomson was rather to find the theoretical solutions to the specific problems arising from Maxwell's electromagnetic theory and, through related simple experiments, to show the adequacy of Maxwell's theory. The gas discharge experiment itself was not carried out in a specific research program (of course, it is true that the work had the vortex theory as its theoretical basis); rather it was to demonstrate the chemical changes occurring in the gas when sparked, and to offer partial explanation based on his own vortex theory. Since 1890, however, Thomson took the gas discharge as a major topic of his experimental research. This is supported by the fact that the treatises published in 1890s, unlike those of the previous years, treated the phenomena of gas discharge, with few exceptions.<sup>67)</sup> He conducted various experiments, from those of electric conduction through hot gases, electric discharge through exhausted tube without electrodes, the electrolysis of steam, to the electrolysis of gases which offered a clue to the relation between gas discharge and chemical combination. And he tried to provide theoretical interpretation on those experiments, believing that such work would throw light on the connection between matter and electricity.

Thomson believed that the passage of electric discharge through gases was accompanied by the dissociation of its molecules and that the migration of charged atoms thus produced constituted electric conduction. Such views, however, suffered a radical change after Röntgen had discovered X-ray in the late 1895. Thomson came to know that it was an atom itself, not a molecule of a gas, that would be split up on the path of the discharge.

## V. 1896-1900

X-rays, discovered by Konrad Röntgen on November 8, 1895, exerted a great influence on Thomson's research on electric discharge. First of all, X-rays changed a gas on their path into a conductor more easily than any other means and made it possible to measure the conductivity of the gas quantitatively, so that they offered

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67) This data are based on the list of treatise in the obituary of Thomson, and *A History of the Cavendish Laboratory, 1871-1910* (London: Longmans, Green & Co., 1910). Of the papers published by Thomson from 1890 to 1895, 18 in total, all but two was on electric discharge through gases.

a useful tool for the investigation of the electric conduction through gases. Until the rays were discovered, a very large electric field, about 30,000 volts/cm in the atmosphere, had to be applied to a gas, in order to make electricity pass through it, or very hot gases such as flames must be used. In these gases, it was extremely difficult to get accurate measurement.<sup>68</sup> In contrast, the gas exposed to X-rays turned to a conductor with the potential difference of 4 or 5 volts. Thus, it was a method of creating conductivity in the gas so stable as to be measured quantitatively.

Thomson had already found, in January of 1896, that X-rays produced a rapid discharge of electricity from a charged plate exposed to them, whether the charge was positive or negative.<sup>69</sup> Next month he pointed out that leakage from a plate could be a "most delicate means of detecting these rays", and of measuring quantitatively the intensity of the rays, and the conductivity of the gas. Especially, leakage of electricity from a charged plate through a tube filled with chlorine was proved to be a very sensitive and convenient method to measure the intensity of X-rays. Thomson used this method in many of his experiments.<sup>70</sup>

Using X-rays, Thomson investigated how the conductivity of gas changes depending on the kind of gas, its pressure, temperature, potential difference, the distance from the discharge tube, and so on.<sup>71</sup> The electric conductivity of a gas was approximately proportional to the square root of the pressure, and it was known that in the cases where the number of dissociated ions was small compared with that of the undissociated molecules, the number of ions was proportional to the square root of the pressure. Therefore, the conductivity of a gas depended only upon the number of ions. A remarkable effect of the variation of potential difference on the conductivity was that the current through a gas increased with potential difference, but soon reached a maximum value.<sup>72</sup> Thomson explained that this effect resulted if chains or aggregates of molecules of a gas were formed around the path of X-rays, which made the charged atoms to migrate more easily.<sup>73</sup>

68) J. J. Thomson, *Recollections*, pp. 325-326.

69) J. J. Thomson, "Longitudinal Electric Waves, and Röntgen's X-rays," *Proc. Camb. Phil. Soc.* 9(1896a), 61.

70) J. J. Thomson, "On the Discharge of Electricity Produced by the Röntgen Rays, and the Effects Produced by These Rays on Dielectrics through which They Pass," *Proc. Roy. Soc.* 59 (1896b), 275.

71) J. J. Thomson & J. A. McClelland, "On the Leakage of Electricity through Dielectrics Traversed by Röntgen Rays," *Proc. Camb. Phil. Soc.* 9(1896c), 126.

72) The current in this state was called a saturation current.

73) But after he, with Rutherford, discovered the destruction of the conductivity of the Röntgenized gas by the passage of electric current, he explained that the saturation must occur if the current destroyed the conducting power of the gas at the same rate as the conductivity was

Thomson interpreted the changes in the property of a gas when exposed to X-rays, on the basis of his previous researches. X-rays, passing through a substance, made it a conductor of electricity, which was due to the splitting of its molecules.<sup>74</sup> Then he found that the conductivity was lost if a current of electricity was sent through the "Röntgenized gas," or the gas exposed to Röntgen rays, and regarded the gas in this state similar to a very dilute solution of an electrolyte. It was known that such a solution ceased conducting after enough electricity had been sent through it to electrolyze all the molecules of the electrolyte, a property quite analogous to that of a Röntgenized gas.<sup>75</sup>

An attempt to understand, through the discharge experiment, the state of matter when traversed by electricity still continued, and in it, too, X-ray was a excellent tool for the quantitative study. Thomson, in collaboration with Rutherford in 1896, derived the velocity of the charged particles in a gas exposed to Röntgen rays.<sup>76</sup> According to their derivation the velocity was about 0.33cm/s for air and this fell far short of 50 cm/s, the value calculated by the kinetic theory of gases. Thus, charged particles in the Röntgenized gas, Thomson thought, were centers of aggregation of a considerable number of molecules.

Meanwhile, the discovery of X-rays greatly stimulated interest in the cathode rays among physicists. As X-rays were emitted from anode when cathode rays fell on it, thus the two rays were clearly related to each other. One should understand the characteristics of cathode ray first to know the cause of X-rays and their properties. Thomson had always approached the problem of cathode rays from the viewpoint that the rays were composed of negatively charged particles. He had already detected the velocity of cathode rays, using rotating mirror, in 1894, and asserted that the velocity of these rays was very small compared with the velocity of light; he concluded that the rays were composed of particles.<sup>77</sup> Even after the discovery of X-rays, Thomson tried, using Perrin's method, to show that the cathode rays really carried negative electricity. In the apparatus of Perrin, a cylinder with a small hole was placed before the cathode, when the cathode rays entered the cylinder through the hole, the cylinder gained a negative charge; if the rays were deflected by a magnet, and escaped the hole, the cylinder remained without the charge. Thomson rearranged the setting and made the cathode rays fall upon the cylinder only when deflected by a magnet, and showed clearly that the

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produced by the Röntgen rays. J.J. Thomson & E. Rutherford, "On the Passage of Electricity through Gases Exposed to Röntgen Rays," *Phil. Mag.* 42(1896d), 393-394.

74) J.J. Thomson, op. cit. (1896b, see footnote 70), 276.

75) *BA Report-1896*, 704; Thomson & Rutherford, op. cit. (1896d, see footnote 73), 393.

76) Thomson & Rutherford, op. cit. (1896d), 402.

77) J.J. Thomson, "On the Velocity of the Cathode-rays," *Phil. Mag.* 38(1894), 358.

emission of electrical particles from the cathode was not an accidental effect accompanying the rays, and the stream of negatively charged particles themselves constituted the cathode rays.<sup>78)</sup>

The discovery of X-rays also made it possible to get cathode rays outside the tube and to study their behavior. It was Lenard who was successful in this work. He placed a plate inside the tube, made of aluminum about 1/100 mm thick, and by this plate he could take cathode rays outside the tube. An interesting observation was that the magnetic deflection of the Lenard rays outside the tube was independent of the density and chemical composition of the outside gas, while varying greatly depending on the pressure of the gas inside the tube. Also, while the absorption coefficients of 'Lenard rays' were rather different for different gases, the ratio of absorption to density remained constant.<sup>79)</sup>

From Lenard's experiments on the absorption of the rays outside the tube, Thomson came to think out the 'corpuscles' in 1897, universal particles constituting matter, and smaller than atoms. Lenard had made the Lenard rays to travel through various gases like hydrogen, air and SO<sub>2</sub>, and had measured the distance which the rays would have to travel before their intensity fell to one half the original values. The rays had traveled about 0.5cm through air at atmospheric pressure. Considering that the mean free path of the molecule of air at this pressure was about 10<sup>-5</sup>cm, the size of the charge-carriers had to be small compared with that of ordinary atoms and molecules. Thomson named such particles as 'corpuscles' and argued that this could explain the results of Lenard's experiments very well. He calculated the ratio of the mass of these corpuscles to the charge carried by them (m/e), and the result about 1.6 x 10<sup>-7</sup>, 1/1000 of the ratio for hydrogen (10<sup>-4</sup>), supported his view substantially.<sup>80)</sup>

The notion of the subatomic particles of matter was quite extraordinary, but it was not completely new. As Thomson himself indicated, chemists had been putting forward the hypothesis that elements were compounds of basic constituents, more basic than atoms. Among them, Prout had believed that atoms of all the elements were composed of hydrogen atoms, and Norman Lockyer advanced the same arguments, based on spectroscopic consideration.<sup>81)</sup>

Measuring the value of the saturation current, Thomson calculated the ionization

78) J. J. Thomson, "On the Cathode-rays," *Proc. Camb. Phil. Soc.* 9(1897a), 243-244; "Cathode-rays," *Proceedings Royal Institution of Great Britain*(1897b), 425.

79) J. J. Thomson, op. cit. (1897b), 429-430.

80) *ibid.*, 429-431. Thomson suggested other method of detecting m/e using the electrostatic deflection in October of the same year. J. J. Thomson, "Cathode rays," *Phil. Mag.* 44(1897c), 300-309.

81) J. J. Thomson, op. cit. (1897b), 431 .

in the gas exposed to X-rays. The saturation current was determined by the condition that the number of ions produced in one second by the rays was equal to the number of ions used up by the current in the same time, and thus was thought to be proportional to the number of ions produced per second. Therefore, if the saturation currents of two gases exposed to rays of the same intensity were known, it was possible to compare the ionization in the two gases. With such assumption, Thomson determined the values of relative saturation currents of various gases, and took them as the ionization constants of molecules of each gas. The saturation currents, or ionization constants of the gases attained through this experiment showed the additive property; if  $2[A]$ ,  $2[B]$  represented the ionizations of the elementary substances  $A_2$ ,  $B_2$  respectively, the ionization of the compound gas represented by the formula  $A_pB_q$  will be equal to  $p[A]+q[B]$ . From the ionization constants of each molecules, Thomson could calculate the ionization constant of the other gases and attained constants not much different from the results of Perrin. The fact that the ionization produced by the rays followed the additive law suggested to Thomson that this ionization was not the separation of one atom from another in the gas molecule but a process occurring in the atom itself.<sup>82)</sup>

From these experimental results, Thomson could establish the theory of the conduction of electricity through gases by charged ions, and could ascertain that the electrification of matter was not due to the splitting of molecules, but due to the splitting of the atoms themselves into ions.<sup>83)</sup> The mass of the carrier of negative electricity was much smaller than that of the atoms, while the mass of the carrier of positive electricity was comparable with the mass of ordinary atoms. The velocity of negative charge carrier was considerably larger than that of the positive charge carrier. From this, Thomson thought he could explain the electrification of matter as follows. An atom is composed of a large number of corpuscles. In the atom, this assemblage of corpuscles is electrically neutral. Because the individual corpuscles behave like negative ions, while the space through which the corpuscles are spread acts as if it had positive electric charge equal in amount to the sum of the negative charges on the corpuscles. The electrification of a gas results from the detachment of corpuscles from the atoms. Detached corpuscles behave like negative ions, each carrying a constant negative charge; the remainder of the atom behaves like a positive ion with a mass large compared with that of the negative ion.

The problem of the relation between matter and electricity, in which Thomson had

82) J.J. Thomson, "On the Connection between the Chemical Composition of a Gas and the Ionization Produced in It by Röntgen Rays," *Proc. Camb. Phil. Soc.* 10(1898), 10-14.

83) J.J. Thomson, "On the Masses of the Ions in Gases at Low Pressures," *Phil. Mag.* 48(1899), 547-569.

been interested since 1883 when he began to study electric discharge through gases, was now solved with the introduction of the 'corpuscle'. The gas discharge proved to be a very appropriate subject of research to reveal the connection between electrical and chemical changes as he had expected. At first he regarded the splitting of molecules into atoms essential to the electric conduction. The research done since 1895, however, proved that the splitting of atoms, not of molecules, into subatomic particles is the real conducting agent.

#### IV. Summary and Conclusion

In the preceding sections, I have surveyed J.J. Thomson's research on gas discharge conducted from 1882 to 1899, dividing it into four periods. Thomson's interest in discharge phenomena was originated in the vortex theory. The discharge phenomena were related to the problem of the effect exerted on the chemical combination and dissociation when a molecule composed of two vortex-ring atoms was disturbed by external electric field. Thomson thought that a molecule would absorb the energy of electric field and be decomposed, but as soon as the disturbances were removed, recombination would take place immediately. The energy reemitted in this process does not return to the field, however, but is emitted altogether in the form of heat or light. This was what Thomson thought the phenomena of discharge. The vortex theory as such was the theoretical basis of his research in his early years at the Cavendish Laboratory since 1884. He carried out experiments to see exactly how the gas discharge takes place; he explained the difference between what happens at the anode and what happens at the cathode with the vortex theory. Thomson confirmed, by experiment, the prediction of the vortex theory that gas molecules are decomposed when the discharge occurs in the gas. The vortex theory predicts that the 'dissociation' of gas molecules and the instantaneous 'dissipation' of the energy of electric field is a necessary condition for the discharge.

But after 1890, Thomson came to recognize the analogy between gas discharge and electrolysis, and began to apply the theory of electrolysis to explain the electric discharge. Since then, his experiments and relevant theoretical considerations had changed slightly but significantly. Thomson realized that the 'dissociation' of molecules is essential in both phenomena, and came to think that the 'dissociation' of field energy is more crucial in the electric discharge through gases. I have argued that Thomson expected, on the basis of this realization, the gas discharge experiment to solve the problem of the relation between matter and electricity. He took the gas discharge as the main topic of his experimental research. This argument

is supported by the fact that Thomson's research in the 1890s, unlike that in the previous years, was focused on electric discharge through gases.

In general, matter in gaseous state has the simplest chemical characteristics, it is also easiest to observe the internal change of matter in gaseous state. Thus, Thomson thought electric discharge to be a suitable means — more suitable than electrolysis — to investigate the chemical problems of matter. By experimenting on gas discharge, Thomson intended to discover the mechanism of chemical combination of matter. He passed electricity through a gas to decompose molecules into atoms and determined the charge of the atoms. From these experiments, he inferred the process by which the chemical combination of matter might take place. He showed, by calculating and measuring the potential energy needed to trigger the chemical reaction, that the reaction took place between aggregates of molecules not between individual molecules. He thought that elucidation of the relation between matter and the charge of atoms would help one to understand many electrical and chemical phenomena, and anticipated it would throw light on the mechanism of gas discharge and chemical combination of matter, and more generally on the composition of matter and mechanism of electric field.

However, Thomson's idea that the electric discharge through gases accompanied the chemical dissociation of gas molecules and the electric conduction can be occurred by the movement of charged atoms changed significantly since Röntgen discovered the X-rays at the end of 1895. Above all, the Röntgen rays provided Thomson with easy experimental methods that make quantitative measurement possible. From Lenard's data on absorption, Thomson had come to the idea that the charge carrier particles must be smaller than the ordinary matter particles like molecules and atoms. Thomson suggested this idea only hypothetically to explain the experimental results, but came to believe that ionization was not the result of splitting of a molecule but a phenomenon occurring inside the atom itself. By 1899 Thomson established the theory of electric conduction through gases by ions and asserted that the electrification of matter was the splitting of atom into more smaller ions.

The relation between matter and electricity, the problem with which Thomson had been concerned since 1883 was now solved with the introduction of the 'corpuscle', but not in the way he had expected. In early years, he had thought that the splitting of molecules into atoms was essential to electric conduction. But as the research had progressed, especially after 1895, it was shown that subatomic particles produced by the splitting of atom itself, not of the molecules, were responsible for the conduction.

From the above discussion, we have seen that the research on the gas discharge began from the concern with the vortex theory, but gradually acquired its own

significance, and came to be recognized as a way to inquire into the relation between matter and electricity. As can be seen from this, Thomson had pursued the problem of electricity and matter consistently from early years, even after discovering the 'electron' in 1897. 1880s and 1890s were an important period in Thomson's career, in which the basic direction of his research had been established. Thomson's interest, in this period, in the relation between matter and electricity continued to the twentieth century.<sup>84</sup>

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84) It is supported by Falconer's argument that another major topic of Thomson's research, cathode rays, was also originated from his concern for the same problem, electricity and matter. I. Falconer, *op. cit.* (1987, see footnote 4), especially 265-267.