

The Experimentation on the Alpha Particle Scattering and the Practice of Quantum Theory*

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요 약

본 논문은 1900년부터 1930년에 이르기까지 알파입자 산란 현상을 둘러싸고 진행되었던 실험과 이와 연관된 실험 장치 및 이론적 설명의 전개 과정에 대해서 다루고 있다. 알파입자 산란 실험은 1932년 이전에 핵물리학 분야에서 핵심적인 연구 주제였다. 러더퍼드 원자 모형, 인공 원소 변환 실험, 러더퍼드 위성 모형, 양자론적 충돌이론 등은 모두 알파입자 산란 실험과 연관되어 진행된 것들이었다. 알파입자 산란 실험이 가능하게 된 데에는 섬광계수기, 전기적 계수 장치, 구름상자 등 핵물리학 초기의 주요 실험장치의 출현이 밑거름이 되었다. 본 논문에서는 피터 잰리슨이 제기한 실험에 있어서 물질적 문화 개념이 구현되는 한 예로서 알파입자를 이용한 초기 산란 실험을 집중적으로 다루고 있다. 무엇보다도 필자는 섬광계수기 장치와 구름상자의 개량에 관한 구체적인 발전의 역사를 세부적으로 분석하고 있다.

실험에 관한 논의뿐만이 아니라 본 논문에서는 양자 충돌 이론은 1930년대에 이르기까지 지속적인 이론상의 실천이 진행되었으며, 이런 이론적 실천의 결과로 알파입자 산란에 대한 양자론적 설명이 실험적으로 입증될 수 있는 수준까지 발전했다는 것을 보이고 있다. 또한 서로 상이한 발전 과정을 겪어 왔던 섬광계수기와 구름상자 등 두 개의 실험장치들에 의해 동시에 알파입자 산란을 설명하는 양자 충돌 이론이 입증됨으로써 충돌 과정에 대한 양자역학적 설명이 마침내 수용될 수 있었다는 것을 밝히고 있다.

주요어: 알파입자 산란, 양자론, 블래킷, 채드윅, 섬광계수기, 구름상자

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In a note on his personal experience of the development of quantum physics N. F. Mott recalled a dramatic situation of 1930 in the field of the α -particle scattering:

I remember on my return to Cambridge my excitement that both Chadwick and Blackett put in hand experiments to verify the effect predicted—twice the Rutherford scattering at 45° —and Rutherford's surprised. "Well, Mott if you think of anything else like that, come and tell me." I think this was one of the few totally unexpected things predicted by quantum mechanics before any sign of it was found experimentally, and impressed Rutherford a good deal.¹⁾

The α -particle scattering was one of main research topics in nuclear physics before 1932. The Rutherford atom model was proposed as a result of the experiment, and his discovery of artificial transmutation of elements was connected with the phenomena of anomalous α -particle scattering. In order to explain these phenomena, Rutherford proposed his satellite model of nucleus, which was finally replaced by the new quantum mechanics of collision processes. Besides, the emergence of three important scientific instruments made the research possible: the scintillation counter, the cloud chamber, and the electrical counter. In the first stage, the scintillation counter was the main instrument to investigate the α -particle scattering. And then, the cloud chamber emerged as a powerful instrument in the research of nuclear physics. The electrical method was finally combined with the cloud chamber method, and the new experimental techniques led to a new era in nuclear physics.

The history of the experimentation on the α -particle scattering shows various lines of instrumental development at the time. In addition to the role in the history of instrument in the 20th century, the scientific research of the α -particle scattering at the time was of importance from even the theoretical standpoint.

** The following abbreviations are used: HSPS, *Historical Studies in the Physical (and Biological) Sciences*; Phil. Mag., *Philosophical Magazine*; Phys. Rev., *The Physical Review*; Proc. Cam. Phil. Soc., *Proceedings of the Cambridge Philosophical Society*; Proc. Roy. Soc. London, *Proceedings of the Royal Society of London*; Verh. Deut. Phys. Ges., *Verhandlungen der Deutschen Physikalischen Gesellschaft*; Zs. f. Phys., *Zeitschrift für Physik*.

1) Notes by Professor Mott (Archive for History of Quantum Physics, University of California at Berkeley).

Physicists mainly practiced the tools of new quantum mechanics, by which they endeavored to find a possible theoretical explanation of the α -particle scattering. Recently, Peter Galison introduced two different traditions in the history of modern experimental physics: The logic tradition represented by the electrical counter, spark chamber, and wire chamber, and the image tradition by the cloud chamber and bubble chamber.²⁾ My survey shows the early stage of the development of these two traditions, especially focussed on the experiment of α -particle scattering.

1. Early survey of the α -particle scattering and the development of the scintillation method

The emergence of the scintillation and the electrical method

During the early 1900s several developments in theory and experiment made it possible to examine the scattering of α -particles: the study of the ionization of molecule gases by collision, the improvement of the quadrant electrometer, and the discovery of the scintillation on zinc sulphide screen by α -particles. From 1896 several physicists noticed that Röntgen and Becquerel rays produced the conductivity in gases. In 1896 J. J. Thomson and E. Rutherford at the Cavendish Laboratory, for instance, discovered that the conductivity approached a maximum, when the electric force was increased.³⁾ At the time, John S. E. Townsend was also a research student at the Cavendish Laboratory under J. J. Thomson. In 1901 Townsend was appointed the first Wykeham Professor of Experimental Physics at Oxford University, and there he discovered that gas molecules could be ionized by collision with ions.⁴⁾ From 1901-1903 Townsend,

2) Peter Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago: University of Chicago Press, 1997).

3) J. J. Thomson and E. Rutherford, "On the Passage of Electricity through Gases exposed to Röntgen rays," *Phil. Mag.* 42 (1896), 392-407. For the study of the conductivity of atmosphere generated by the Becquerel ray, see J. Elster and H. Geitel, "Versuche an Becquerelstrahlen," *Ann. d. Phys.* 66 (1898), 735-740; "Weitere Versuche an Becquerelstrahlen," *Ann. d. Phys.* 69 (1899), 83-90.

4) John S. Townsend, "The Conductivity produced in Gases by the Motion of Negatively

with the aid of P. J. Kirkby, published a series of papers, where they investigated the ionization of neutral gases by collision in a strong electric field.⁵⁾ Though some physicists accepted the existence of electron at the time, Townsend, however, did not explain the ionization of molecule gases by using the electrons. He thought that negatively charged ions, not electrons, mainly caused the ionization of gases. Despite his reluctance to accept the role of electrons Townsend's extensive studies on the ionization of neutral gases by collision of charged ions provided plenty of experimental results which enabled electrical methods of counting of charged particles.

By 1901 F. Dolezalek in Berlin-Halensee succeeded in developing a very sensitive quadrant electrometer which was later indispensable for the discovery of the transmutation of elements by Rutherford and Soddy.⁶⁾ Until the time the Thomson quadrant electrometer could measure the voltage up to 0.1 volt. Reducing the internal capacitance of the electrometer, Dolezalek could increase the sensitivity of the electrometer to the level of 0.0001 volt.

In 1903, on the other hand, two remarkable discoveries of flashes on zinc sulphide screen appeared, which later played an important role in the history of nuclear physics. On March 19, 1903 William Crookes presented his observation that the emanations of radium produced the scintillations by their bombardment of a screen of Sidot's hexagonal blend (a phosphorescent zinc sulfide crystal).⁷⁾ Thus, radioactive emanations could be indirectly rendered visible through a simple microscope. Independently, Julius Elster and Hans Geitel in Wolfenbüttel also observed that the atmospheric emanation around thorium hydroxide caused

Charged Ions," *Phil. Mag.* 1 (1901), 198-227.

- 5) John S. Townsend and P. J. Kirkby, "Conductivity produced in Hydrogen and Carbonic Acid Gas by the Motion of Negatively Charged Ions," *Phil. Mag.* 1 (1901), 630-642; P. J. Kirkby, "On the Electrical Conductivities produced in Air by the Motion of Negative Ions," *Phil. Mag.* 3 (1902), 212-225; John S., "The Conductivity produced in Gases by the aid of Ultra-Violet Light," *Phil. Mag.* 5 (1903), 389-398; John S. Townsend, "The Genesis of Ions by the Motion of Positive Ions in a Gas, and a Theory of the Sparking Potential," *Phil. Mag.* 6 (1903), 558-618.
- 6) F. Dolezalek, "Ueber ein einfaches und empfindliches Quadratenelektrometer," *Zeitschrift für Instrumentenkunde* 21 (1901), 345-350. For the role of this electrometer in discovering the transmutation of elements, see Thaddeus J. Trenn, *The Self-Splitting Atom: The history of the Rutherford-Soddy collaboration* (London: Taylor & Francis, 1977), pp. 28-32.
- 7) William Crookes, "Certain Properties of the Emanation of Radium," *Chemical News* 87 (1903), 241; "The Emanation of Radium," *Proc. Roy. Soc. London* 71 (1903), 405-408.

the phosphorescence from the screen of Sidot's blend. On 27 March 1903, they published some note which supported Crookes's observation.⁸⁾ At that time, however, Crookes, and Elster and Geitel, did not use the explicit name of α -particle.

By 1903 the classification of radioactive rays, namely, alpha-beta-gamma rays, was gradually stabilized among scientists.⁹⁾ As the classification of radioactive rays was established, scientists soon perceived that α -particles from the source of radiation like radium or polonium mainly produced the scintillations. In 1906 Rutherford at the McGill University in Montreal observed that the brilliancy of the scintillations produced by the γ -rays in zinc sulphide decreased rapidly as the range of the particles was cut down by the use of absorbing screen. At the time, however, he could not count the number of the scintillation.¹⁰⁾ In 1908 Erich Regener in the Physical Institute of the University of Berlin estimated the quantity of the elementary electrical charge by using the scintillation method.¹¹⁾ This was the first successful experiment of counting the number of α -particles by using a zinc sulfide screen.

On 22 February 1908 Otto Hahn informed Rutherford of Regener's paper. At the time Ernest Rutherford and Hans Geiger in Manchester also were engaged in a similar topic. Two days later Rutherford wrote to Otto Hahn:

It was very good for you to tell me of Regener's paper. I read the first one of his on the probability estimate of the number of particles. The general idea was not new to me as Geiger—one of my men—had finished a paper on the determination of the experimental error in comparison with the calculated one. I am rather surprised that the method of counting scintillations gives somewhere about the right result. I should have anticipated that the chances were that the number of scintillations would be smaller than the number of α -particles. It will be interesting to see how closely Regener can determine the number. Our counting experiments are going alright and I hope in a few days

8) J. Elster and H. Geitel, "Über die durch radioaktive Emanation erregte scintillierende Phosphoreszenz der Sidot Blende," *Phys. Zs.* 4 (1903), 439-440.

9) For Rutherford's role in the classification scheme of radioactive rays, see Thaddeus J. Trenn, "Rutherford on the Alpha-Beta-Gamma Classification of Radioactive Rays," *ISIS* 67 (1976), 61-75.

10) E. Rutherford, "Retardation of the α -Particle from Radium in passing through Matter," *Phil. Mag.* 12 (1906), 134-146, here p. 145.

11) Erich Regener, "Über Zählung der α -Teilchen durch die Szintillation und die Größe des elektrischen Elementarquantums," *Verh. Deut. Phys. Ges.* 10 (1908), 78-83.

to be able to say pretty definitely how the theoretical and experimental numbers agree. The method is going fine. By using a sensitive electrometer I could easily make an α -particle swing the spot of light off the scale.¹²⁾

At the time Rutherford and Geiger also noticed the validity of the scintillation method in counting the number of charged particles. In their experiment of counting the number of α -particles, however, the doubt arose whether every α -particle produced a scintillation. To remove such possible errors, they developed another way to detect the alpha particle scattering: The electrical method of counting the number of α -particles.¹³⁾ To detect a single α -particle by measuring the ionization they used a pair of quadrants of a Dolezalek electrometer. Their preliminary experiment to detect a single particle by its direct ionization, however, was beset with numerous difficulties like the problem of a long period of swing in very sensitive electrometer. To overcome the difficulties they used the principle of magnification of ionization by collision in a strong electric field, which Townsend and his collaborator had already worked out. After observing even a small electric effect, they compared the number of scintillations produced on a zinc sulfide screen with the number of α -particles counted by the electric method. Their results clearly confirmed that each α -particle produced a scintillation:

Considering the probability error, the agreement between the electrical and optical methods of counting, no doubt, closer than one would expect. The result, however, brings out clearly that within the limit of experimental error, each α -particles produces a scintillation on a properly prepared screen of zinc sulphide. The agreement of the two methods of counting the α -particles is in itself a strong evidence of the accuracy obtained in counting the α -particles expelled per gramme of radium by the electrical method. It is now clear that we have two distinct methods, one electrical and the other optical, for detecting a single α -particle, and that the employment of either method may be expected to give correct results in counting the number of α -particles.¹⁴⁾

On the other hand, the counting of the scintillation belonged to a very tedious

12) Rutherford Papers ADD. 7653 at the Cambridge University Library.

13) Ernest Rutherford and Hans Geiger, "An Electrical Method of Counting the Number of α -Particles from Radio-active Substance," *Proc. Roy. Soc. London A* 81 (1908), 141-161.

14) *Ibid.*, p. 158.

task. First, the experiments should be made at night in a dark room. According to Rutherford and Geiger, it was difficult to continue counting for more than two minutes at a time, as the eye became fatigued.¹⁵⁾ Regener also told that an observer needed more than 15 minutes, in order that observer's eyes could reach enough dark-adaptation.¹⁶⁾ The continuous counting was reliable only for 5-10 minutes.

The electrical method, however, still had the difficulties in removing the disturbances of the electrometer needle ascribed to a slight natural radioactivity. Furthermore, the inertia of a quadrant electrometer restricted the counting number of α -particles. The electrical method needed some improvements, in order that it became a major instrument to measure the scattering of α -particles. In 1913 Geiger, taking the newly established position of director of the laboratory of radium research at the Physikalisch-Technische Reichsanstalt in Berlin, devised a new counter, so-called "point counter" where the whole working of the apparatus depended on the point of the needle. Geiger's new device was able to count even β particles as well as α particles.¹⁷⁾ From 1917 Alois F. Kovarik in Yale University improved the electrical method by adopting a three electrode vacuum tube amplifier, newly developed in America.¹⁸⁾ But until 1930 only a few scientists used the electrical method in their experiments of the scattering of α -particles.¹⁹⁾

The α -particle scattering and its interpretations

During 1905-1906, Rutherford at McGill University in Montreal obtained an

15) *Ibid.*, p. 157.

16) E. Regener, "Über Zählung der α -Teilchen durch die Szintillation und über die Größe des elektrischen Elementarquantums," *Sitzungsberichte der preussischen Akademie der Wissenschaften (Berlin)* 38 (1909), 948-965, here p. 955.

17) Hans Geiger, "Über eine einfache Methode zur Zählung von α - und β -Strahlen," *Verh. Deut. Phys. Ges.* 15 (1913), 534-539. For the development of the point counter and coincidence counting see Peter Galison, *op. cit.*, pp. 438-454.

18) Alois F. Kovarik, "New Methods for Counting the Alpha and Beta particles," *Phys. Rev.* 9 (1917), 567-568; "A Device for the Automatic Registration of the α - and β -Particles and γ -Ray Pulses," *Phys. Rev.* 13 (1919), 153-154.

19) In 1926 rather an unknown scientist in Canada used the electrical method. See D. C. Rose, "The Scattering of Alpha particles through Small Angles," *Proc. Roy. Soc. London A* 111 (1926), 677-690.

evidence of the scattering of α -particles.²⁰⁾ In a series of papers he showed that the image of a narrow slit produced by the α -rays on a photographic plate broadened out when the slit was covered with a thin sheet of mica, while a well-defined image was obtained in vacuum with the uncovered slit. Rutherford argued that this broadening of the photographic trace could be explained by assuming a slight scattering or deflection of the path of the α particle in passing through matter. Thus the magnitude of this scattering could be determined by the photographic method. B. Kučera and B. Mašek, at the University of Prague, investigated the feature of secondary rays when α -rays struck on a metal surface. By using the ionization method, they suggested in 1906 that the behavior of secondary α -rays could be explained by the α -ray scattering. They argued that alpha rays were diffusely scattered when they penetrated through a metal sheet, and that the scattering power of a metal was probably proportional to the square root of the atomic weight.²¹⁾

W. H. Bragg in the University of Adelaide countered the assumption of the α -ray scattering. He argued that the effects, observed by Kučera and Mašek, could be explained by ascribing them to the slight alteration in the stopping-power of two metals when inverted.²²⁾ Despite Bragg's rejection the existence of α -ray scattering was further confirmed by Lise Meitner.²³⁾

Hans Geiger tried to give a direct evidence of the actual existence of the scattering of α -particles in passing through matter, whether gaseous or solid.²⁴⁾ Associated with the paper of Rutherford and Geiger on the electrical method of counting α -particles, Geiger determined the magnitude of the scattering of α -particles by using the scintillation method. Geiger's experiment led to the discovery of the existence of a diffuse reflection of the α -particles performed by Geiger and E. Marsden.²⁵⁾ In their experiment they showed that despite the high

20) E. Rutherford, "Some Properties of the α Rays from Radium," *Phil. Mag.* 11 (1905), 166-176, here p. 174; E. Rutherford, "Retardation of the α -Particle from Radium in passing through Matter," *op. cit.*, pp. 143-145.

21) B. Kučera and B. Mašek, "Über die Strahlen des Radiotellurs III: Die Sekundärstrahlung der α -Strahlen," *Phys. Zs.* 7 (1906), 650-654, esp. 653-4.

22) W. H. Bragg, "The Influence of the Velocity of the α particle upon the Stopping Power of the Substance through which it passes," *Phil. Mag.* 13 (1907), 507-516.

23) Lise Meitner, "Über die Zerstreuung der α -Strahlen," *Phys. Zs.* 8 (1907), 489-491.

24) H. Geiger, "The Scattering of the α Particles by Matter," *Proc. Roy. Soc. London A* 81 (1908), 174-177.

velocity and the mass of the α -particles some of the reflected α -particles can be turned within a thin layer of 6×10^{-5} cm of gold through an angle of 90° , and even more.²⁶⁾ In the case of platinum, especially, that of the incident α -particles about 1 in 8,000 appeared to be diffusely reflected.²⁷⁾

In the next experiment on the α -particle scattering Geiger tried to determine the most probable scattering angle in different thickness and diverse materials with its atomic weight, and obtained some remarkable results.²⁸⁾ First, he could show that the most probable angle of scattering increases for small thickness approximately proportional to the square root of the thickness of matter. Especially, he observed that the probable angle which an α -particle is turned in passing through an atom is proportional to its atomic weight, and the most probable scattering angle in the case of gold is about $1/200$ of a degree. Besides, Geiger observed the variation of scattering with the velocity of α -particles, and found that the most probable angle is inversely proportional to the third power of the velocity.²⁹⁾

In 1911 Rutherford proposed his new atom model based on the experiments of Geiger and Marsden.³⁰⁾ In this paper he compared his theory with the scattering of α -particles through large angles, the variation of diffuse reflection with atomic weight of the radiator, and the most probable scattering angle through a thin metal plate. The controversy between the Manchester and the Cavendish approach also shows the difference of the experimental tools and the theories. Whereas the Manchester group supported the Rutherford atom model by using the scattering of α -particles and the scintillation method, the Cavendish group supported the Thomson model by using the scattering of α -particles and the ionization chamber method.³¹⁾

25) H. Geiger and E. Marsden, "On a Diffuse Reflection of the α Particles," *Proc. Roy. Soc. London A* 32 (1909), 495-500.

26) *Ibid.*, p. 498.

27) *Ibid.*, p. 499.

28) H. Geiger, "The Scattering of the α Particles by Matter," *Proc. Roy. Soc. London A* 83 (1910), 492-504.

29) *Ibid.*, p. 504.

30) E. Rutherford, "The Scattering of α and β Particles by Matter and the Structure of the Atom," *Phil. Mag.* 21 (1911), 669-688. See also John L. Heilbron, "The Scattering of α and β Particles and Rutherford's Atom," *Archives for History of Exact Sciences* 4 (1968), 247-307.

Geiger and Marsden tested the Rutherford atom model, and in 1913 they published their results.³²⁾ Until then, experimentalists had measured only the variation with atomic weight of scattering material. But Geiger and Marsden counted in their new experiment the number of α -particles emerging from a scattering foil at an angle with the original beam varying from 5° to 150° . Their experiment could show that the result is in good agreement with the Rutherford theory, the main feature of which is that there exists at the center of the atom an intense highly concentrated electrical charge.³³⁾ The main difference between the earlier and the later experiments was to test the variation of scattering with angle.

Along with the experimental test C. G. Darwin in Manchester elaborated the Rutherford model and connected it with some experimental results. In 1912 he checked most probable angles of scattering in passing through matter with its atomic weight.³⁴⁾ Next, in 1914, he extended the Rutherford theory to the case of collision of α -particles with light atoms.³⁵⁾ He also examined the possibility that some other laws of force like the inverse cubic law might give the same result as that of Geiger and Marsden. In his papers Darwin estimated an upper limit to the size of atomic nuclei like hydrogen and helium from the distance of closest approach between the α -particle and nucleus at less than 10^{-13} cm.³⁶⁾

An anomalous effect and the development of the scintillation method

Besides the α -particle, a hydrogen particle also produced a visible scintillation. The scintillations produced by the hydrogen particles differed little from those produced by α -particles except that they are not so intense. In examining the scintillations, experimenters had a possibility of detecting the hydrogen particle that collides with the α -particle. Marsden in Manchester attempted to determine

31) J. A. Crowther, "On the Transmission of β Rays," *Proc. Camb. Phil. Soc.* 15 (1910), 442-458; "On the Scattering of Homogenous β rays and the Number of Electrons in the Atom," *Proc. Roy. Soc. London A* 84 (1910), 226-247.

32) H. Geiger and E. Marsden, "The Laws of Deflexion of α Particles through Large Angles," *Phil. Mag.* 25 (1913), 604-623.

33) *Ibid.*, p. 610 and p. 623.

34) C. G. Darwin, "A Theory of the Absorption and Scattering of the α Rays," *Phil. Mag.* 23 (1912), 901-920.

35) C. G. Darwin, "Collision of α Particles with Light Atoms," *Phil. Mag.* 27 (1914), 499-506.

36) *Ibid.*, p. 506.

the exact ranges of the hydrogen particles produced by α -particles.³⁷⁾ His experiment of 1914 was in hydrogen at high pressure so that the α -particles had a smaller range. He found that the absorption relations of the hydrogen particles by various metals held for the hydrogen particles similar to Bragg's law of absorption for α -particles, where the absorption is proportional to the square root of atomic weight.

In 1905 W. H. Bragg and R. Kleeman had found that the loss of velocity of α particles in traversing any atom is nearly proportional to the square root of the atomic weight.³⁸⁾ Their experiment also showed that the loss in the case of a complex molecule is proportional to the sum of the square roots of the weights of the constituent atoms. In 1910 Geiger, on the other hand, found that the range of α -particle in air is proportional to the third power of the velocity. In 1914 Darwin treated theoretically the loss of velocity of α -particles in passing through matter.³⁹⁾ In his experiment of hydrogen Marsden compared his experimental results with Darwin's formula for the scattering of α -particles with the hydrogen atom.

Qualitatively, Marsden's results agreed well with Darwin's calculation. It seemed desirable, however, to make quantitative measurements of the number and distribution of the hydrogen particles. For the next goal, Marsden, with aid of his collaborator W. C. Lantsberry, undertook an investigation of the long-range particles emitted from the source of Radium Emanation.⁴⁰⁾ So as to make the detection more easily, they used a thin film of paraffin wax, rich in hydrogen. The film of wax was placed round α -ray tube. Marsden and Lantsberry observed that the experimental results were several times greater than anticipated by Darwin's formula. At first glance, they considered that "the source itself was emitting long-range particles capable of scintillating, and that these were scattered in the wax, thus causing the disturbance."⁴¹⁾ After investigating these long-range particles, they concluded that hydrogen particles are emitted from the source,

37) E. Marsden, "The passage of α -particles through hydrogen," *Phil. Mag.* 27 (1914), 824-830.

38) W. H. Bragg and R. Kleeman, "On the α Particles of Radium, and their Loss of Range in passing through various Atoms and Molecules," *Phil. Mag.* 10 (1905), 318-340.

39) C. G. Darwin, "Collision of α Particles with Light Atoms," *Phil. Mag.* 27 (1914), 499-506.

40) E. Marsden and W. C. Lantsberry, "The passage of α -particles through hydrogen. II," *Phil. Mag.* 30 (1915), 240-243.

41) *Ibid.*, p. 241.

namely the radioactive atoms themselves, and that, unlike α -particles, their velocities are not uniform. Their experiments, however, were interrupted by the departure of Marsden in early 1915, when Marsden moved to New Zealand to fill the professorship of physics in Victoria College, Wellington. First, in New Zealand, Marsden could not find the sufficient quantity of radium to carry out the nuclear experiments. Moreover, the war prevented him from managing further experiments.

During the war Rutherford continued Marsden's experiments in more detail, as the pressure of war-work permitted. He focused his experiment on the phenomenon that the number of scintillations from hydrogen is much greater than is to be expected on the simple theory. This line of experiment led him to a remarkable conclusion that the hydrogen atom is a product of radioactive transformation. After the war Rutherford published a series of papers on collision of α -particles with light atoms like hydrogen, nitrogen, and oxygen.⁴²⁾

In the first paper Rutherford examined close collisions between α particles and hydrogen atoms. Rutherford thought that in the experiments of Geiger and Marsden on the large angle scattering of heavy atoms like those of gold the law of inverse square held up to the distance of the order of 3×10^{-12} cm. In the collisions of α particles with light atoms like those of hydrogen, however, the atomic nuclei were able to approach still closer to a distance of the order of 3×10^{-13} cm. Rutherford observed that in such close collisions, the number and distribution of the hydrogen atoms are entirely different from those calculated on the assumption that the nuclei repel each other according to the law of inverse square. Rutherford, furthermore, investigated the collisions of α -particles with air, and he noticed the another surprising anomalous effect: When dried oxygen or carbon dioxide was admitted into the vessel the number of scintillations diminished to the amount to be expected. When dried air was introduced, however, the number of scintillation was increased. After examining other possibilities, Rutherford concluded "that the nitrogen atom is disintegrated under the intense forces developed in a close collision with a swift α particle, and that the liberated hydrogen atom formed a constituent part of the nitrogen nucleus."⁴³⁾

Rutherford proposed a model of the nucleus in order to explain his experiment

42) E. Rutherford, "Collision of α Particles with Light Atoms," *Phil. Mag.* 37 (1919), 537-587.

43) *Ibid.*, p. 586.

of collision of α particles with light atom. He anticipated, for example, that the nitrogen nucleus consisted of three helium nuclei each of atomic mass 4 and either two hydrogen nuclei or one of mass 2. This model of the nitrogen nucleus later developed into so-called Rutherford's satellite model of the nucleus.⁴⁴⁾

Rutherford's experiments provided new possibilities of discovering more definite information about the structure of the nucleus. According to Rutherford the nucleus of helium was made up of two electrons and four protons. C. G. Darwin worked out the collision relations for all possible models of the α -particle which gave integrable orbits.⁴⁵⁾ He showed that a square nucleus, in which the hydrogen nuclei were arranged at the four corners and the two electrons together at the center, would give a field of force very similar to that of a bipole. The collision relation of the bipole was roughly similar to that deduced from Rutherford's experiments. Darwin, however, left the decision as to the shape and size of the nucleus, until accurate experiments were made.⁴⁶⁾ One of noteworthy facts is that Darwin at the time did not use the quantum theory for explaining the collision process. He believed that the quantum theory was connected with a theory of radiation.⁴⁷⁾

Meanwhile, Rutherford and his collaborators elaborated the experiments of the anomalous scattering by refining the scintillation method, and they found a clear effect which deviated from the inverse-square law. In 1920 James Chadwick, at the time a Wollstan student of Gonville and Caius College in Cambridge, improved the scintillation method by varying the speed of the rotating wheel which could change the time-distribution of the scintillations.⁴⁸⁾ He measured the charges of the nuclei of platinum, silver, and copper by the direct measure depending on the scattering of α -particles. He also observed that the inverse square law around the platinum nucleus held accurately in the region around 10^{-11} cm from the nucleus.

44) For Rutherford's satellite model of the nucleus see Roger H. Stuewer, "Rutherford's satellite model of the nucleus," *HSPS* 16:2 (1986), 321-352.

45) C. G. Darwin, "The Collisions of α -Particles with Hydrogen Nuclei," *Phil. Mag.* 41 (1921), 486-510.

46) *Ibid.*, p. 510.

47) *Ibid.*, p. 503.

48) J. Chadwick, "The Charge on the Atomic Nucleus and the Law of Force," *Phil. Mag.* 40 (1920), 734-746.

Unlike the heavy element like platinum, the light element showed the divergence from the inverse-square law at small distances of approach. Rutherford's experiment of 1919 found the divergence. But his experiments were of a preliminary nature, and were not carried out to any high accuracy. With the aid of the recent improvements of the optical instruments Chadwick and E. S. Bieler could count even the weak scintillations produced by the hydrogen particles more easily and more clearly. Chadwick and Bieler elaborated their setup, by using a new microscope consisted of a Watson holoscopic objective and a low-power eyepiece. In 1921 Chadwick and Bieler found that in the collisions of high-velocity α particles with hydrogen atoms the forces between the α -particle and the hydrogen nucleus do not vary according to the inverse square law.⁴⁹⁾ In the following experiment of Rutherford and Chadwick the microscope had been further improved with the aid of the Kellner eyepiece.⁵⁰⁾

In 1924 Bieler investigated the scattering of α -particles by aluminium and magnesium nuclei for angles of scattering between 20° and 100° , and found a clear divergence from the inverse-square law.⁵¹⁾ He concluded that the divergence followed approximately an inverse fourth-power attractive force. In 1925 Rutherford and Chadwick, concluding a series of experiments of their own, explained the anomalous effect by invoking Rutherford's so-called satellite model of nucleus. The abnormal scattering, they argued, could be explained by assuming that the target nuclei consisted of a complex system consisting of a charged central core surrounded by a satellite distribution of positive and negative charges.⁵²⁾

49) J. Chadwick and E. S. Bieler, "The Collisions of α Particles with Hydrogen Nuclei," *Phil. Mag.* 42 (1921), 923-940.

50) E. Rutherford and J. Chadwick, "The Disintegration of Elements by α Particles," *Phil. Mag.* 44 (1922), 417-432.

51) E. S. Bieler, "The Large-Angle Scattering of α -Particles by Light Nuclei," *Proc. Roy. Soc. London A* 105 (1924), 434-450. See also Bieler, E. S., "The effect of deviations from the inverse square law on the scattering of α -particles," *Proc. Camb. Phil. Soc.* 21 (1923), 686-700.

52) E. Rutherford and J. Chadwick, "Scattering of α -particles by Atomic Nuclei and the Law of Force," *Phil. Mag.* 50 (1925), 889-913.

2. Blackett and the cloud chamber method

The early development of the cloud chamber

In 1911 C. T. R. Wilson elaborated an apparatus making visible the tracks of ionizing particles through gas.⁵³⁾ Wilson's apparatus originated from the tradition of the "mimetic experimentation" in Victorian England.⁵⁴⁾ Many scientists in Victorian England attempted to reproduce natural phenomena like clouds, fog, and the blue sky, in their laboratories, and Wilson's cloud chamber could develop while re-creating the meteorological phenomena in the controlled world of the laboratory. Wilson obtained some photographs of the clouds condensed on the ions produced along the tracks of α -particles. In the following experiment he enlarged his cloud chamber in size and gave ample room for the longest α -ray.⁵⁵⁾ By using the elaborated instrument he could obtain clearer photographs of the trails of α -particles. Above all, Wilson observed that the α -rays are generally straight over the greater part of their length, but that some of them are bent, often abruptly, in the last of their course.

In making the cloud chamber, it was very difficult to keep a volume of air constantly at a high supersaturation. Furthermore, the expansion took place so suddenly that it was very difficult to determine this interval with accuracy. In Rutherford's first year at the Cavendish Laboratory in Cambridge he had a Japanese pupil called Takeo Shimizu. Rutherford encouraged Takeo Shimizu to use Wilson's cloud chamber to examine the α -particle collisions with nitrogen nucleus.⁵⁶⁾ Takeo Shimizu made a rapid and automatic Wilson apparatus in 1921.⁵⁷⁾

53) C. T. R. Wilson, "On a Method of making Visible the Paths of Ionising Particles through a Gas," *Proc. Roy. Soc. London A* 85 (1911), 285-288. For his earlier paper see C. T. R. Wilson, "On the Condensation Nuclei produced in Gases by the Action of Röntgen Rays, Uranium Rays, Ultra-violet Light, and other Agents," *Philosophical Transactions of the Royal Society London* 192 (1899), 403-453.

54) Peter Galison, *op. cit.*, pp. 73-75. See also Peter Galison and Alexi Assmus, "Artificial Clouds, Real Particles" in David Gooding, Trevor Pinch, and Simon Schaffer (eds.), *The uses of experiment* (Cambridge: Cambridge University Press, 1989), pp. 225-274.

55) C. T. R. Wilson, "On an Expansion Apparatus for making Visible the Tracks of Ionising Particles in Gases and some Results obtained by its Use," *Proc. Roy. Soc. London A* 87 (1912), 277-292.

56) P. M. S. Blackett, "The Old days of the Cavendish," *Rivista del Nuovo Cimento* 1 (1969),

Modifying Wilson's original cloud chamber, he substituted for the isolated sudden expansion of Wilson's apparatus a continuous series of expansions and compressions produced by a piston moving with simple harmonic motion. Shimizu's apparatus had the advantage of taking large number of photographs within a reasonable time. With the new elaborated apparatus Shimizu photographed about 3,000 α -ray tracks, and he observed eleven branched α -ray tracks.⁵⁸⁾ At the time the Cambridge Scientific Instrument Company assisted Shimizu to patent the automatic cloud chamber and produced it under a royalty agreement with him.⁵⁹⁾ Takeo Shimizu, however, had to go back to Japan for family reason, and he could not participate in the further development of the cloud chamber.

P. M. S. Blackett, who was graduated from Cambridge University in 1921, and worked as a researcher in the Cavendish Laboratory, continued Shimizu's work and partly modified the apparatus.⁶⁰⁾ In Blackett's new expansion chamber the reciprocating mechanism in Shimizu's chamber was replaced by a simple spring action. This shared with Wilson's original design the advantage of securing a very sudden repeated expansion as frequently as required. Blackett's new apparatus enabled him to investigate collisions between α -particles and the nuclei. What is noteworthy is that he could observe the collisions of α -particles of such a low velocity that did not approach closer to the nucleus. Until that time no particles had been detected by scintillation method with certainty with velocities less than about $0.4 V_0$, where V_0 was the initial velocity of the α -particles from radium C. The Wilson expansion chamber method, therefore, had the advantage of investigating collisions of these α -particles of low velocities. Blackett, however, could not discover any anomalous effect in collisions of α -particles of low velocities. The inverse square law still held between the nuclei and the α -particle,

xxxii-xxxix, here xxxiv.

- 57) Takeo Shimizu, "A Reciprocating Expansion Apparatus for Detecting Ionising Rays," *Proc. Roy. Soc. London A* 99 (1921), 425-431; "A Preliminary Note on Branched α -Ray Tracks," *Proc. Roy. Soc. London A* 99 (1921), 432-435.
- 58) Takeo Shimizu, "A Preliminary Note on Branched α -Ray Tracks," *op. cit.*, p. 435.
- 59) M. J. G. Cattermole, *Horace Darwin's Shop: A History of The Cambridge Scientific Instrument Company 1878 to 1968* (Bristol: Adam Hilger, 1987), p. 78.
- 60) P. M. S. Blackett, "On the Analysis of α -Ray Photographs," *Proc. Roy. Soc. London A* 102 (1922), 294-318; "The Study of Forked α -Ray Tracks," *Proc. Roy. Soc. London A* 103 (1923), 62-78.

when their distance apart lay between about 7×10^{-12} and 10^{-9} cm for argon, and 3×10^{-12} and 5×10^{-10} cm for air.⁶¹⁾ In modifying the Shimizu's chamber, Blackett gradually abandoned the Shimizu's continuously moving piston in favor of one producing a series of isolated and sudden expansions. In effect, he readopted the Wilson's original technique. In 1924 Blackett's apparatus reached its final form at the early stage in the development of his cloud chamber.⁶²⁾

The original experiment of Rutherford and later those of Rutherford and Chadwick treated the disintegration of element by α particles, and their experiments showed that fast α particles, by close collision, could eject protons from the nuclei of many light elements.⁶³⁾ In particular, the protons from boron, nitrogen, fluorine, sodium, aluminum, and phosphorus had great ranges, and were emitted in all directions relative to the velocities of bombarding α -particles. The scintillation method used in these experiments could give no direct information about the motion after the collision, and could detect the proton alone. Blackett, therefore, intended to investigate the ejection of protons from nitrogen nuclei and took photograph of the collision between an α -particle and a nucleus of hydrogen, helium or nitrogen. In order to photograph the artificial disintegration of elements, an automatic apparatus was essential. Blackett's new automatic chamber could make one expansion and took one photograph every ten or fifteen seconds.⁶⁴⁾ He eventually could take nearly 50,000 photographs, giving in all photographs of about 800,000 alpha ray tracks.⁶⁵⁾ In this experiment, unlike the former one, he could found that the inverse-square law between α -particles and nitrogen nuclei does not hold at small distances of approach:

61) P. M. S. Blackett, "On the Analysis of α -Ray Photographs," *op. cit.*, p. 317.

62) P. M. S. Blackett, "The Ejection of Protons from Nitrogen Nuclei, Photographed by the Wilson Method," *Proc. Roy. Soc. London A* 107 (1925), 349-360.

63) E. Rutherford, "Collision of α Particles with Light Atoms," *Phil. Mag.* 37 (1919), 537-587; E. Rutherford and J. Chadwick, "The Artificial Disintegration of Light Elements," *Phil. Mag.* 42 (1921), 809-825; Rutherford, E. and J. Chadwick, "The Disintegration of Elements by α Particles," *Phil. Mag.* 44 (1922), 417-432; "Further Experiments on the Artificial Disintegration of Elements," *Proceedings of the Physical Society* 36 (1924), 417-422. Here Rutherford interpreted that the H nuclei liberated from the elements probably existed as satellites circulating in orbits round the main nucleus.

64) P. M. S. Blackett, "The Ejection of Protons from Nitrogen Nuclei, Photographed by the Wilson Method," *op. cit.*, p. 350.

65) P. M. S. Blackett, "An automatic cloud chamber for the rapid production of alpha ray photographs," *Journal of Scientific Instruments* 4 (1927), 433-439, esp. p. 434.

Amongst the 270,000 alpha particles of 8.6 cm range, whose tracks have been photographed, 14 have been deflected through angles between 45° and 90° . On the inverse-square law the number would, on the average, be about 12—in rough agreement with the observations. On the other hand the number deflected elastically through angles greater than 90° is found to be 8, while the average number on the inverse-square law would be about 1.5. This indicates that the inverse-square law between alpha particles and nitrogen nuclei does not hold for such intimate collisions.⁶⁶⁾

The technical improvement of the cloud chamber

After finishing the experiment on the ejection of protons from nitrogen nuclei Blackett improved his cloud chamber still further.⁶⁷⁾ He thought that his apparatus was not entirely satisfactory either in design, construction or reliability. To produce good tracks the cloud chamber had to fulfill some technical conditions:⁶⁸⁾ First, the gas in the chamber before the expansion must be saturated with water vapor and be at a uniform temperature. Second, no condensation ions must be present at an expansion other than those produced at the correct moment during the expansion by the rays from radioactive sources. Third, the supersaturation must be susceptible to fine and easy control. Finally, the alpha rays must be prevented by a shutter from entering the chamber till sufficient supersaturation is attained. Perceiving that the Shimizu apparatus could not fulfill the first three conditions, he began to design a more complicated cycle of operations for a small automatic cloud chamber. In the case of a small automatic chamber of 6 cm diameter, the shortest length of the cycle was about 13 seconds. Besides, he constructed an alpha ray shutter so as to prevent the alpha rays from prematurely entering the chamber.

While Blackett elaborated the new cloud chamber, he also carried out the experimentation with the apparatus. Blackett and E. P. Hudson at King's College investigated the elasticity of the collision of α particles with hydrogen.⁶⁹⁾ In 1926

66) P. M. S. Blackett, "The Ejection of Protons from Nitrogen Nuclei, Photographed by the Wilson Method," *op. cit.*, p. 355.

67) P. M. S. Blackett, "An automatic cloud chamber for the rapid production of alpha ray photographs," *op. cit.*

68) *Ibid.*, pp. 434-435.

69) P. M. S. Blackett and E. P. Hudson, "The Elasticity of the Collision of Alpha particles

Adolf Smekal had suggested that inelastic collisions could occur where a nucleus was only deformed without disintegration.⁷⁰⁾ Blackett and Hudson wished to find inelastic collisions in the new cloud chamber, but they failed to photograph the occurrence of such type of collisions within the limits of experimental error.⁷¹⁾

In 1929 Blackett developed another larger automatic cloud chamber.⁷²⁾ In this new apparatus he used the same cycle of operation as before, but the period of cycle was somewhat longer, about 17 seconds, instead of 13 seconds. Blackett adopted as a timing device a mechanical oscillograph by which the movement of the piston and the shutter could be simultaneously photographed. Blackett also improved the arrangement of cameras to photograph artificial disintegrations of nuclei.⁷³⁾ A camera of the type used by Shimizu and Blackett consisted of two separate cameras at right angles. With the help of T. Smith of the National Physical Laboratory Blackett modified the original arrangement: In this arrangement the direction of the lens axis passed through the center of the chamber and made only a small angle, i.e., 8.5° with the normal to the photographic plate. He adopted this method by using the new type of tilted lens camera which was supplied by the Cambridge Scientific Instrument Company.⁷⁴⁾ The lenses were tilted in such a way that the whole plane of the chamber was in sharp focus on both film. This method made it possible to work with much wider beams of alpha particles than with the original type of apparatus.

3. The quantum theory and the development of instruments

The development of the quantum theory of collision processes in Cambridge

with Hydrogen Nuclei," *Proc. Roy. Soc. London A* 117 (1928), 124-130.

70) A. Smekal, "Anomale Zerstreuung von α -Strahlen," *Phys. Zs.* 27 (1926), 383-385.

71) P. M. S. Blackett and E. P. Hudson, "The Elasticity of the Collision of Alpha Particles with Hydrogen Nuclei," *op. cit.*, p. 129.

72) P. M. S. Blackett, "On the automatic use of the standard Wilson chamber," *Journal of Scientific Instruments* 6 (1929), 184-191.

73) P. M. S. Blackett, "On the Design and Use of a Double Camera for Photographing Artificial Disintegrations," *Proc. Roy. Soc. London A* 123 (1929), 613-629.

74) *Ibid.*, p. 615.

The theoretical development concerning the α -particle scattering belonged to a typical example of theoretical practice in the field of the new quantum mechanics. Many physicists including Rutherford and Darwin interpreted the anomalous α -particle scattering as a classical phenomenon, and they did not use the quantum theory in describing collision processes. Blackett, though he was an experimentalist, was interested in the development of the quantum theory of collision processes. In treating the electron impacts Blackett used the quantum theory for the first time.⁷⁵⁾ Despite Rutherford's opposition to Blackett's decision to spend the academic year 1924-1925 in Germany, Blackett visited Göttingen and worked with James Franck.⁷⁶⁾ They published a joint paper on the dissociation of hydrogen molecules by bombarding them with electrons.⁷⁷⁾ Blackett seemed to be satisfied with his study in Germany and became acquainted with the new quantum theory of collision processes as well. After returning to Cambridge, he attempted to explain the deviation from the inverse square law in α -particle scattering on the basis of wave mechanics.⁷⁸⁾

Eventually Max Born in Göttingen opened a new way to a theoretical explanation of the anomalous α -particle scattering by applying wave mechanics to collision processes.⁷⁹⁾ The new Göttingen approach to the quantum theory of collision processes was introduced to Cambridge by P. Dirac who had worked in Göttingen in 1927.⁸⁰⁾ Encouraged by Dirac, N. F. Mott began to develop systematically the quantum theory of the scattering of particles.⁸¹⁾ Meanwhile, J.

75) P. M. S. Blackett, "Angular Momentum and Electron Impact," *Proc. Camb. Phil. Soc.* 22 (1924), 56-66.

76) For the description of this situation see Bernard Novell, "Patrick Maynard Stuart Blackett, Baron Blackett, of Chelsea," *Biographical Memoirs of Fellows of the Royal Society* 21 (1975), 1-113, esp. pp. 10-11.

77) P. M. S. Blackett and J. Franck, "Anregung von Spektren des Wasserstoffs durch Elektronenstoß," *Zs. f. Phys.* 34 (1925), 389-401.

78) P. M. S. Blackett, "The limits of classical scattering," *Proc. Camb. Phil. Soc.* 23 (1927), 698-702.

79) For the development of the quantum theory of collision processes in Göttingen see Gyeong Soon Im, "Experimental Constraints on Formal Quantum Mechanics: The Emergence of Born's Quantum Theory of Collision Processes," *Archive for History of Exact Sciences* 50 (1996), 73-101. See also Giuseppe Bruzsaniti, "Classical and quantum approaches to anomalous scattering," *Physica* 30 (1993), 449-475.

80) P. Dirac, "Über die Quantenmechanik der Stoßvorgänge," *Zs. f. Phys.* 44 (1927), 585-595.

81) N. F. Mott, "The Solution of the Wave Equation for the Scattering of Particles by a

R. Oppenheimer at the Caltech in 1928 emphasized that previous works on collision had neglected transitions to states in which atomic and impacting electrons exchange places.⁸²⁾ Next year N. F. Mott elaborated Oppenheimer's argument by using the exclusion principle of Pauli.⁸³⁾ Here he argued that in the case of the collision between an electron and an atom, the wave function must be anti-symmetrical in the coordinates of all the electrons present. If the two particles are identical, i.e., two electrons or two α -particles, the wave functions used must be anti-symmetrical and symmetrical in the coordinates of the two particles. Thus the new scattering law was quite different the formula derived from the classical theory.

In the next paper Mott treated the collision between two particles possessing spin, such as electrons, and also between two particles without spin, such as α -particles.⁸⁴⁾ Until the time, the evidence of the band spectrum of the helium molecule showed that α -particles have no spin and obey the Einstein-Bose statistics. Mott, according to the new scattering theory, calculated the ratio of the quantum theory scattering to the classical Rutherford scattering. The ratio had a maximum at 45° , the maximum value of the ratio being 2.⁸⁵⁾ The intensity of the scattering at 45° , namely, was double the classical for all values of the velocity. This ratio was a good criterion for deciding whether the quantum mechanical calculation agreed with the experimental results or not.

Two crucial experiments

Although Mott had already calculated that the maximum ratio of the quantum theory scattering to the classical Rutherford scattering at 45° is 2, unfortunately, in the works done until the time on the scattering of α -particles in helium, the quantum mechanical effect was obscured by the classical structure effect which

Coulombian Centre of Force," *Proc. Roy. Soc. London A* 118 (1928), 542-549.

82) J. R. Oppenheimer, "On the quantum theory of electronic impact," *Phys. Rev.* 32 (1928), 361-371.

83) N. F. Mott, "The Exclusion Principle and Aperiodic Systems," *Proc. Roy. Soc. London A* 125 (1929), 222-230.

84) N. F. Mott, "The Collision between Two Electrons," *Proc. Roy. Soc. London A* 126 (1930), 259-267, received on 7 November 1929.

85) *Ibid.*, p. 264.

Rutherford mentioned in his satellite-model of the nucleus. In 1927 Rutherford and Chadwick had investigated the scattering of α -particles by helium using the scintillation method.⁸⁶⁾ In this paper Rutherford explained the anomalous scattering by assuming a complex system of nucleus. Oppenheimer in Göttingen, however, tried to explain the deviation from the inverse-square law on the basis of quantum theory, and Rutherford rejected Oppenheimer's approach.⁸⁷⁾ The Rutherford and Chadwick's experiment of 1927 had not been pursued to α -particle energy below the range of α -particles of 2.6 cm of air for the scattering angles 40° and 50° . At this velocity of α -particles they obtained the value 1.3 for the ratio of observed to calculated scattering. At the time, the value was regarded sufficiently close to the classical ratio 1.0 rather than the quantum-mechanical ratio 2.0. To show the quantum effect clearly, much slower α -particles had to be used.

In 1930 Chadwick overcame the limit of velocity of α -particle by an ingenious comparison method, using argon and helium.⁸⁸⁾ The experiment was the last in which Chadwick used the scintillation counter. So as to obtain an incident beam of particles of low velocity, absorbing sheets of mica were placed over the source. In those cases, however, it was very difficult to estimate directly the quantities depending on the velocities of incident particles. Chadwick could avoid the difficulties by comparing the scattering in helium with the scattering in argon under the same condition. Below the range of α -particles of 2.94 cm Chadwick estimated the ratio of the observed scattering in helium to that calculated on the classical theory. The ratio first reached a maximum of 2.66 at the range of 2.04 cm, finally 2.12 at the range of 1.2 cm approaching the predicted value of 2.0. From this new experiment Chadwick concluded: "Since the present experiments show conclusively that the field of force around the normal α -particles is spherical, the asymmetry shown at small distances of collision can be due to nothing else but a distortion of the structures of the particles."⁸⁹⁾

After Chadwick's new experiment had finished, a new version of Rutherford's

86) E. Rutherford and J. Chadwick, "The Scattering of α -particles by Helium," *Phil. Mag.* 4 (1927), 605-620.

87) *Ibid.*, p. 616.

88) J. Chadwick, "The Scattering of α -Particles in Helium," *Proc. Roy. Soc. London A* 128 (1930), 114-122.

89) *Ibid.*, p. 122.

Radioactive substances and their radiations was published by Rutherford, Chadwick, and C. D. Ellis.⁹⁰⁾ Later H. S. W. Massey wrote: "In his contribution Chadwick was critical at time of some of Rutherford's published work but, after discussion, Rutherford allowed it all to pass without alteration. The book remains a classic."⁹¹⁾

Blackett and his student F. C. Champion investigated the scattering of much slower α -particles by helium, using Blackett's new elaborated cloud chamber.⁹²⁾ The lowest velocity of α -particles in Chadwick's experiment corresponded to 8.5×10^8 cm per second. Slower particles could not be utilised owing to the difficulty of counting the scintillation. By using a cloud chamber Blackett could reduce the velocity of α -particles to 10^8 cm/sec, corresponding to the velocity eight times smaller than was possible with the scintillation method. Blackett and Champion thought that a clear test of Mott's scattering theory were possible at such low velocities. For the slow particles the closest distance of approach was so large that there seemed to be no possibility of any deviation from the inverse square law complicating the scattering.

With the automatic Wilson chamber, containing a mixture of helium and oxygen Blackett and Champion found 428 forks among 56,520 photographed tracks. First, the observed distribution of the intensity of the scattering was in complete qualitative agreement with Mott's theory, which had predicted a maximum of double the classical for 45° . Blackett and Champion also checked a quantitative comparison, and they concluded that their experimental results were in excellent agreement with Mott's theory. The observed distribution of the intensity of the scattering was a probable one if the quantum theory of the scattering was correct, but a most improbable one if the classical theory was right.

90) Ernest Rutherford, James Chadwick, and C. D. Ellis, *Radiations from Radioactive Substances* (Cambridge: Cambridge University Press, 1930).

91) H. S. W. Massey and N. Feather, "James Chadwick," *Biographical Memoirs of Fellows of the Royal Society* 22 (1976), 11-70, here p. 19. See also Ernest Rutherford, James Chadwick, and C. D. Ellis, *op. cit.*, pp. 276-277.

92) P. M. S. Blackett and F. C. Champion, "The Scattering of Slow Alpha Particles by Helium," *Proc. Roy. Soc. London A* 130 (1931), 380-388.

4. Epilogue

The experimentation on the α -particle scattering developed as a result of the emergence of the three instruments: the scintillation counter, the cloud chamber, and the electrical counter. The scintillation method, emerging in 1903, could be used to detect α -particle scattering from 1906. Rutherford and Geiger devised the electrical method for counting the number of α -particle in 1908. But the method needed some technical improvement, so as to become a major instrument in the field of nuclear physics. It could not be widely used to examine α -particle scattering until the late 1920s. The cloud chamber method, devised in 1911, could be used for the investigation of α -particle scattering. Nevertheless, automatic cloud chambers were elaborated from the early 1920s.

On the other hand, the α -particle scattering provided a theoretical practice in the field of the new quantum mechanics. Until 1921 physicists including Darwin did not use the quantum theory for explaining the collision process. They thought that the quantum theory was largely related to a theory of radiation. Quantum mechanics became to be extensively used for explaining collision processes from 1926. A clear quantum mechanical description of α -particle scattering, however, could not emerge until November 1929.

The story of the α -particle scattering shows the multiplex aspects of theory and instrument. First, the experimentation on the α -particle scattering was conditioned by the level of technical improvement of instruments. Each scientist, furthermore, had particular preference in exploiting the instrument and in adopting the theory. Rutherford largely favored the scintillation counter method and the classical theory. Blackett, a technical specialist in the field of the cloud chamber, did not hesitate to accept the new quantum theory of collision process developing in Göttingen. Unlike the discoveries of positron and neutron, the electrical method played no significant role in the experiment of α -particle scattering.