CHAPTER I

EXPERIMENTS—AND THE TYPES OF INFORMATION OBTAINED

§ 1. Introduction: calculated and measured magnitudes. The atomic theory of matter, as an element in speculative philosophy, is of considerable antiquity; as a scientific formulation it is to be attributed in the first place to Dalton.\(^a\) From a consideration of the relative combining weights of elementary substances and the pressure-volume-temperature relations for isolated portions of matter in the gaseous state,\(^b\) Dalton was led to the idea of atoms, identical amongst themselves when a single chemical substance is in question, but differing in respect of weight from one substance to another. Similarly, macroscopic phenomena, in particular capillarity and cohesion in liquids, provided the data which led Young\(^c\) to an early and reasonable estimate of the “size” of an atom. Later Kelvin\(^d\) made several such estimates on the basis of similar material. In each case the crude experimental data consisted of mass and length determinations: masses of chemical substances, linear dimensions of glass vessels, lengths of columns of mercury or of pointer movements over fixed scales. Transition to the sub-microscopic took place on paper—in the course of the arithmetic—or in the mind of the interpreter. The concept atom-of-matter arose in this way, and the necessary consequence of accepting such a concept—the fact that a certain degree of spatial extension had to be assigned to the atom—received numerical expression merely as a result of the calculations. The further history of this concept is the story of modern physics in one of its major aspects. As that history is briefly sketched in the sections

\(^a\) Dalton, New System of Chemical Philosophy, Part I, 1808; Part II, 1810.

\(^b\) Ronce and Harden, New View of the Origin of Dalton’s Atomic Theory, 1806.

\(^c\) Young, “Cohesion of fluids”, Encyclopaedia Britannica, 5th edition, 1816; Collected Works, 1, 461, 1855.

\(^d\) Kelvin, Baltimore Lectures, pp. 279–84, 1904.
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which follow it will be seen how the notion of spatial extent is
particularised and the idea of structure is introduced, under
the necessity of interpretation for more detailed experiments.
Moreover, the main concern of the present book begins only
after the broad outlines of this structural pattern have been
accepted and it becomes necessary to particularise still further
and assign structure to the atomic nucleus. Parts II, III and
IV deal exclusively with the experiments which have made
necessary these more recondite developments in the interpret-
tative scheme.

At the very beginning, however, it is worth while insisting
that the crude data of any scientific experiment, whatever its
aim, must be measured physical quantities of roughly a
single order of magnitude. Apparatus is designed to bring
within compass of human perception and measurement
significant evidence of events of the astronomical or the sub-
atomic order; in the quantitative interpretation of these
results powers of ten arise in the course of arithmetical
multiplication and division—sometimes with alarming facil-
ity. Only the engineer is left in a position to evaluate by
direct apprehension the import of his conclusions. The
astronomer and the modern physicist, at opposite extremes
of the scale, almost naturally discard inconvenient powers of
ten for ease in forming such mental pictures as are required
for successful thinking. But they invite danger whenever
they forget what they have discarded. To such danger the
nuclear physicist is particularly liable; he measures in terms
of centimetre scales and gram “weights” and is just as far
from quantities of this order of magnitude in stating the mass
of the proton, for example, as the astronomer is in giving the
distance of the spiral nebulae—the atoms in one gram of
hydrogen in line at one centimetre intervals would stretch for
nearly a million light years! It is the object of this chapter,
then, to describe precisely the types of measurement made in
experiments on nuclear physics, as it will be of succeeding
chapters of Part I to enquire how far the interpretation of
such experiments may be carried in terms of the concepts
of macroscopic physics—the ideas of the engineer and the

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astronomer—or to what extent an entirely new point of view may be necessary. This new viewpoint is embodied in the wave mechanics of the theorist.

For convenience in description, and also because some approximation to chronological order is thereby attained, the experiments in question may be classified roughly as follows: (a) experiments concerning the properties of radioactive material or of matter subjected to the action of radiations from radioactive substances, (b) investigations of matter in general by the method of mass spectroscopy, (c) investigations of matter by the method of optical spectroscopy, and (d) experiments involving the bombardment of matter by artificially accelerated particles.

§ 2. Experimental methods in radioactivity. Radioactivity is a spontaneous activity of matter, first noticed in 1896,\(^a\) which is confined, in general experience, to a relatively small number of elementary substances of high atomic weight. This activity is shown in a persistent, if gradually dwindling, emission of energy\(^b\) which may be set in evidence in a number of ways. Thus the active material and portions of surrounding matter increase in temperature if thermally insulated from other bodies in the neighbourhood, volumes of gas previously possessing very feeble electrical conductivity become conducting, certain phosphorescent substances emit light and unexposed photographic plates become developable under the action of the radiations. Closer analysis discloses further the mechanism of these effects.

Conductivity, for example, may first be studied as a volume effect, the current through the gas being measured by the rate of charge of the quadrants of a sensitive electrometer, or by some similar arrangement. It is thus investigated in its dependence on the collecting field, on the distance of the preparation, the amount of screening matter interposed, or on the time. From another angle of approach it appears that the processes of expenditure of energy respon-

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\(^b\) "Radiation" is the term generally applied to the vehicle by which energy is given out by matter.
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sible for the conductivity are localised in the gas along linear elements; in the finer analysis, therefore, these processes do not occur uniformly throughout the volume. The development of the expansion chamber by C. T. R. Wilson\textsuperscript{a} made this analysis possible. Here the sample of gas under observation is rendered temporarily supersaturated with water vapour and it is found that, in circumstances wherein an exactly similar sample of dry gas would show electrical conductivity, the volume of moist gas exhibits the condensation of vapour in “tracks”. There is every reason to conclude\textsuperscript{b} that these tracks represent the initial distribution in the gas of carriers of electricity such as are responsible for the conductivity. The distribution itself is most simply explained if it be assumed that the tracks delineate precisely the geometrical paths of single particles, most of which are emitted directly from the source, although some clearly are liberated from the gas in the chamber. By an obvious application of terms the particles emitted from the source are referred to as primary\textsuperscript{c} particles, those set free in the body of the gas as secondary particles. All these particles lose kinetic energy in passing through the gas. Ionisation, that is the separation of opposite charges initially combined in the form of electrically neutral gas molecules, would obviously be impossible without some such expenditure of energy. Qualitatively, individual tracks show great differences in respect of density, length and degree of straightness (Plate I(a)). If the explanation in terms of ionising particles be adopted, at least two different types of primary particle must be postulated. This is a conclusion which, in actual fact, had been reached long before the expansion method was applied to the problem. Rutherford\textsuperscript{d} had shown that some such assumption was necessary to explain the dependence of the saturation current through a given volume of gas on the amount of screening matter inter-

\textsuperscript{c} This does not represent strictly the current usage of the term “primary $\beta$ particle”; however further refinement is impossible at the present stage (see footnote, p. 38).
\textsuperscript{d} Rutherford, \textit{Phil. Mag.} 47, 109, 1899.
Plate I

Figure a

Figure b
Radioactivity

posed between the radioactive preparation and the gas. In this way he had distinguished between "\(\alpha\)" radiation, the effect of which—the major effect of the source—was cut off by a small amount of matter, and "\(\beta\)" radiation, which could be detected through much greater thicknesses. The investigation was carried farther by Bragg who measured the saturation current between two parallel metal grids separated by a small distance in air, as a function of the distance of the source. He showed that the ionising effect of the \(\alpha\) radiation ceased abruptly at a particular distance. In this way the idea of \(\alpha\) particle "range" arose—some years before expansion chamber photographs provided direct evidence in the form of straight dense tracks having well-defined end points. To this early period, also, belong certain other experiments of Rutherford. Carrying the absorption method farther than previous observers had done, he found a small residual effect through thick screens which was but slowly reduced as the thickness of absorber was still further increased. Villard had already had photographic evidence of this in 1900. Both effects are to be attributed to a third type of primary radiation ("\(\gamma\)" radiation). Later researches have shown that the secondary ionising particles set in evidence by expansion chamber photographs result from the action of this radiation on the material through which it passes. These photographs illustrate clearly the reason for the great penetrating power of the \(\gamma\) radiation: the individual processes by which it loses energy occur at relatively long intervals in the course of its propagation through matter. It is sometimes convenient to refer to it as a non-ionising radiation, however obvious it is that such a description is not entirely exact.

Closer analysis of the action of the radiations on phosphorescent materials in many cases shows only that the phenomena involved are of considerable complexity, but with

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\(a\) The experimental method here exemplified is generally referred to as the "absorption" method, a graph of ionisation current against amount of interposed matter being termed an absorption curve.

\(b\) Bragg and Kleeman, *Phil. Mag.*, 6, 728, 1904.


\(d\) Villard, *Comptes rendus*, 130, 1010, 1178, 1900.
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one or two substances it has resulted in the discovery of an effect which has been put to much practical use. Crookes\textsuperscript{a} showed that the general luminosity of phosphorescent zinc sulphide under the impact of the radiations consisted of individual flashes of light separately visible to the dark-adapted eye, when suitably aided. Simplest conditions obtain when the phosphorescent material is placed within the range of the $\alpha$ particles from a weak source. Then the flashes of light (scintillations) may be regarded as due to the impact of individual $\alpha$ particles on the screen. In this process a portion of the energy of the particle, having first been used, presumably, in ionisation and excitation of the atoms of solid matter traversed, is eventually radiated as visible light. Regener\textsuperscript{b} first made use of this effect to register the arrival of $\alpha$ particles on a screen of determined area; in applying it in this way he has been followed by almost all the workers in radioactivity of the period 1909–29. During the last few years, however, equivalent electrical methods have been developed, having much greater power. These permit of the continuous registration of the passage of single particles, by amplification of their ionising effects. What is finally observed is no longer a small portion of the energy of the particle, as in the scintillation method, but energy from an external supply released by a type of trigger action controlled by the production of ionisation by the particle in its passage through the counting chamber. Thus a considerable deflection of a spot of light on a scale, or a loud sound in a telephone receiver, may result. In this connection two types of amplification must be distinguished. The distribution of applied electric field in the counting chamber may be such that the cumulative process of ionisation by collision occurs in the gas, so that considerably more charge is collected than is liberated by the passage of the particle itself—in this case a relatively small degree of further amplification by the electrical recording system is sufficient—or the initial ionisation may be simply collected by means of a smaller field, when the whole

\textsuperscript{a} Crookes, Proc. Roy. Soc. 71, 405, 1903.
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of the necessary amplification must be obtained from the electrical circuits employed. Each arrangement has its own advantages and disadvantages. Smaller initial amounts of ionisation may be detected with the former arrangement ("point-counter", etc.), but the latter (ionisation chamber and valve amplifier) is more easily made "proportional", that is, arranged to give a final effect which provides a direct measure of the amount of charge liberated by the particle. As applied to experiments in radioactivity the point counter (or tube counter) is more suited to the investigation of $\beta$ particle effects, the ionisation chamber and amplifier to phenomena in which $\alpha$ particles are involved.

Photography is an important aid both to electrical counting methods and also when the expansion chamber is employed. In the case of the expansion chamber it is obvious that this must be so; in the other case it is frequently of interest to know not only the number of particles registered within a given time, but also, as is possible with proportional amplifiers, the amount of ionisation which each particle has produced. In such circumstances photographic registration of the oscillograph deflections becomes a great convenience. But it has also been mentioned that radioactive radiations exert a direct action on the sensitive grains in a photographic emulsion. This fact is responsible for two methods of employing photographic materials as primary detectors in certain investigations. In the first method the radioactive matter is incorporated in the emulsion or is brought in contact with it. Then, on development, short rows of reduced silver grains appear which must be interpreted as essentially $\alpha$ particle tracks (see Plate I ($b$)). The method is extremely crude, in that the tracks are short (about $5 \times 10^{-3}$ cm.) and never contain very many grains (40, at most, with specially prepared emulsions), but it has the convenience for some purposes that the final image gives the integrated effect of

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the radiation, which may be too feeble to be detected by other means. On the other hand it is not applicable to the study of the individual particles constituting radioactive β radiation. The second method of employing photographic plates directly is to use them as detectors when canalised beams of particles are under investigation in vacuo—for they may be introduced into evacuated vessels without finally impairing the “vacuum”. The deflection of such a beam of particles under the action of electric or magnetic fields may thus be studied in terms of the movement of the “image” formed on the plate by the normal incidence of the beam. This method will be further discussed in the section on mass spectrum analysis.

These methods then, simple measurement of ionisation current (or of heating effect—which is occasionally used), counting of scintillations, direct exposure of the photographic plate, the method of the expansion chamber and the various arrangements of counter and proportional ionisation amplifier, enable a detailed study to be made of the properties of the radiations from radioactive substances. Supplemented by chemical methods they provide information concerning the changes which occur in the materials themselves concurrently with the emission of the radiations. Precisely similar methods are employed when attention is chiefly concentrated on the changes produced by these radiations in matter on which they fall. In such cases the amount of material actually affected is always much too small for purely chemical methods to be of any avail; any information which is obtained must, therefore, in the first place be information concerning the (secondary) radiations which are emitted in the course of the

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b Frequently ionisation chambers are employed which contain gas at several atmospheres pressure. This modification introduces many advantages for certain types of work; cf. Hoffmann, Z. Physik, 42, 565, 1927; Tarrant, Proc. Roy. Soc. 128, 345, 1930; Gray, ibid. 130, 524, 1931; also Florance, Phil. Mag. 25, 172, 1913.

c Russell (A. S.), An Introduction to the Chemistry of Radioactive Substances, 1922.

d See, however, p. 126.