New Aspects of Radioactivity.*

By Dr. C. D. ELLIS, F.R.S.

γ-RAYS AND NUCLEAR STRUCTURE.

UNTIL a few years ago, the fundamental problems of physics were those concerned with the structure of the atom. The nucleus was necessarily often referred to, but only in relation to its effect on the behaviour of the electrons in the atom. It was found that for most purposes the net charge, Ze, was a sufficient description of the nucleus. Within, however, the last three years, the whole attitude of physicists to this problem has changed ; on one hand, our knowledge of those phenomena which depend on the intimate structure of the nucleus has been greatly increased : on the other hand, wave mechanics has proved to be eminently suitable for a theoretical attack on this problem, and has already provided a solution of some of the outstanding problems.

Of the many lines of investigation which have been developed, not the least interesting is that of the characteristic electromagnetic radiation that can be emitted by radioactive nuclei. These radiations are termed the γ-rays and are in general of considerably shorter wave-length than the X-rays. They bear the same relation to the structure of the nucleus as do the ordinary optical and X-ray spectra to the structure of the electronic system of the atom, but there is this one point of difference. The optical and X-ray spectra can conveniently be studied for a series of elements because the process of excitation is under control, but it is only in a few isolated cases that it has yet been possible to excite a nucleus by external agencies to emit characteristic radiation. Some of the radioactive bodies, however, emit these radiations spontaneously, since the process of disintegration leaves the newly formed nucleus in an excited state and able to emit its characteristic radiation. The nuclear spectra have therefore only been examined in detail for those radioactive bodies which happen to emit them, and it has been impossible as yet to find any general laws governing the arrangement of these spectra by noting the similarities in the spectra from a succession of different nuclei.

The result of this was that, until a few years ago, while there was a great deal of information about the nuclear spectra of several radioactive bodies, it was still impossible to associate this with any definite feature of the structure. Recently the position has changed greatly, and it now seems possible to view in the nuclear level systems which can be deduced from the γ-ray measurements the characteristic stationary states of α-particles or protons in the nucleus, and to associate such level systems directly with the ground states deducible from other evidence.

METHODS OF INVESTIGATING THE γ-RAYS.

A simple method that was of great importance in the early days of radioactivity was to investigate the absorption of the radiation emitted by a particular body by placing a radioactive source at some distance from an electroscope and observing how the ionisation decreased when successive sheets of some material such as aluminium or lead were interposed. It was frequently possible to analyse the resulting absorption curve into a series of simple exponential curves, and thus to obtain a general idea of the different components of the complex radiation. Methods such as this could never yield very precise information, and they have now been superseded by more accurate methods.

The crystal method, in the forms used for X-rays, has been applied with considerable success to γ-rays.[1] In one respect the technique is simpler, since in place of the X-ray tube with all the apparatus necessary to run it, it is only necessary to use a fine tube containing the radioactive material, but in other respects the experiments are far more difficult. Owing to the very short wave-length, of the order of 40 X.U. to 4 X.U., the glancing angles are extremely small, and not only is the adjustment of the apparatus considerably more difficult but it is also impossible to measure the wave-length with much accuracy. Further, in comparison with an X-ray tube, the normal amount of radioactive material constitutes an extremely weak source of radiation. As a result it has not yet been possible to push this method when using photographic registration beyond 16 X.U. Recently Steadman [2] has devised an arrangement, using an electrical counter in place of a photographic plate, which may overcome some of these difficulties.

The method which has given us most of our information is based on the photoelectric effect. The general principle is very simple and is as follows.[3] A tube containing the radioactive body, the γ-rays of which are under investigation, is placed inside a small tube of some material of high atomic weight, such as platinum. In their passage through the platinum, the γ-rays eject groups of photoelectrons the energies of which are connected with the frequency of the γ-rays by the Einstein law. Thus the γ-ray of frequency ν will lead to the ejection of a series of groups of electrons of energies $h\nu$-K_{Pt}, $h\nu$-L_{Pt}, etc., according to whether the conversion occurs in the K, L, etc., state of the platinum atoms. This electronic emission can be separated out into a corpuscular spectrum by the usual method of semicircular magnetic focusing. It is usual to register these spectra photographically, and there is not a great deal of difficulty in analysing them and deducing the corresponding γ-rays, since in most cases it is only the electronic group from the K level which is sufficiently intense to give a detectable effect. The general application of the method is greatly limited by the fact that the photographic impression of the groups of electrons always shows as a broad, rather diffuse band. The reason is that, although the photoelectrons are ejected from the platinum atoms with sharply defined energies, only those from the surface

* Substance of two lectures delivered at the Royal Institution on Nov. 4 and 11.

of the tube actually emerge with their full velocity. Those from the lower layers are retarded in their passage out, and cause the diffuse character of the band.

Fortunately, the radioactive atoms themselves provide us with much more favourable opportunities for observing this photoelectric conversion, by what is termed internal conversion. This is by itself an extremely interesting phenomenon, and will be referred to in detail later. For the present purpose it is convenient to describe it as follows. When a radioactive nucleus emits a quantum $h\nu$ of radiation, this does not always escape as such from the atom but may be absorbed by the electronic structure of the atom in its passage out. This internal conversion follows the usual photoelectric laws, and thus a radioactive body which emits γ-rays will also emit a corpuscular spectrum similar in every respect to that coming from the platinum tube already mentioned, except that the energies are now $h\nu$-K_{rad}, $h\nu$-L_{rad}, . . . The result is in principle in no way different from the previous case where the γ-rays were converted in the platinum, but the importance of this phenomenon for determining the wave-length of the γ-rays depends on the following facts. If a normal amount of radioactive material is deposited on the surface of a fine wire, the actual number of atoms is so small that the layer is in general less than one atom deep. The electrons liberated by this internal photoelectric effect therefore all escape with their full energy and give extremely sharp lines on a photographic plate, in striking contrast to the broad bands obtained by the normal external photoelectric effect. There is the further advantage that the probability of this internal conversion is so great that measurable lines can be obtained with far shorter exposures than by the other method, and the effects of γ-rays are detectable which are so weak as to be quite unattackable by the other method.

The γ-rays of many radioactive bodies have been analysed by this method, and the main features of the characteristic nuclear spectra are known. The accuracy with which the frequencies can be determined is, however, considerably lower than that realised with X-ray spectra. Even in the case of the bodies radium B and radium C, which have been extensively investigated, the relative frequencies are probably not known to much better than one part in five hundred, and the absolute error may be greater. The chief cause for this lies in the difficulty of obtaining a homogeneous magnetic field over a large area.

INTENSITIES OF THE γ-RAYS.

An important method[4] of investigating the intensities has been developed by Skobeltzyn, based on the Compton effect of the γ-rays. A narrow pencil of γ-rays is allowed to pass through an expansion chamber and the recoil electrons liberated by the Compton effect of the γ-rays are observed in the usual manner. In addition, a magnetic field parallel to the axis of the chamber is applied at the moment of expansion, so that the tracks of the recoil electrons are curved by an amount depending on their velocity. By observing both the curvature and the direction of emission of the recoil electrons, it is possible to associate each electron with a γ-ray of definite frequency. A statistical study is made of the relative number of the recoil electron tracks, and from a knowledge of the general laws of scattering it is possible to deduce the relative intensities of the γ-rays.

Owing to a variety of experimental causes, the resolution of the method is not very high, and the effect of two neighbouring γ-rays cannot always be clearly separated. This disadvantage, however, is far outweighed by the definiteness of the results about the intensity distribution throughout the spectrum, and by the fact that the method detects weak γ-rays equally efficiently as strong γ-rays. The interpretation involves a knowledge of the laws of scattering, but there is both a reasonable theoretical foundation and internal evidence from these experiments which combine to render the uncertainties due to this cause of little importance at present.

The photoelectric method has been applied to determine the intensities of the γ-rays by Ellis and Aston.[5] The corpuscular spectra liberated from the radioactive atoms themselves by the internal conversion are clearly of no use in this connexion, since the relative intensities of the groups depend upon the unknown laws of internal conversion. If, however, the corpuscular spectrum ejected from platinum is observed, we are concerned only with the normal photoelectric effect. Supposing that the X-ray absorption results could be extrapolated to the γ-ray region, it would then be possible to deduce the intensities of the γ-rays from the intensities of the corresponding electronic groups. It is, however, precisely this point which is doubtful, and the accuracy of this method is at present limited by the accuracy of the empirical formula which it was necessary to assume for the photoelectric method. The method, however, has one extremely important advantage, which is, that if a γ-ray is sufficiently intense to give a measurable corpuscular group, then the intensity of this group can be determined independently of neighbouring weak γ-rays. It will be seen that these two methods are really complementary, one supplying the deficiencies of the other. The γ-rays of radium B and radium C are the only ones that have yet been intensively investigated, but the results seem consistent, and we know not only the general distribution throughout the spectrum but also the individual intensities of all the strong γ-rays.

The results that have just been mentioned referred to the relative intensities of the γ-rays, and in the analogous case of X-rays or optical spectra this would be all that could be stated. However, in the case of the radioactive bodies it is possible to define and to deduce the absolute intensities. This depends upon the fact that the process of excitation is due to the disintegration of the atom. When a nucleus disintegrates, the departure of the disintegration particle, α or β, may leave the nucleus in an excited state, and its subsequent return to its normal state is the cause of the emission of the γ-rays. The γ-rays are, therefore, emitted only after this disintegration, and it is possible to define the absolute intensity of a γ-ray as the average number of quanta emitted per disintegration. It follows that the absolute intensity of any γ-ray cannot be greater than unity. The simplest way of deducing these absolute intensities is to make use of the measurements of the total amount of energy emitted in the form of γ-rays. Knowing both the frequencies and the relative intensities of the γ-rays, it is easy to calculate the average number of quanta of each frequency emitted per disintegration. This further step has already been carried out for the γ-rays of radium B and radium C.

If we now review the information that we possess about the γ-rays of radium B and C and anticipate that which we shall no doubt in time possess about the rays of other bodies, it will be seen that on the whole it compares very favourably with that available about X-ray spectra. The accuracy of the wave-length determinations is certainly much lower, but we have this important information about the absolute intensities. For example, a prominent γ-ray of radium C has a wave-length of 20·2 X.U., which may be in error by one part in five hundred to even one part in three hundred, but on the other hand, we can say that a quantum of this radiation is emitted by the nucleus on the average twice in every three disintegrations.

Applications to the Structure of the Nucleus.

The preceding account will have shown the extent to which the spectroscopy of the γ-rays has advanced. Its application to the problem of nuclear structure is only at the beginning, but it is already possible to indicate the possible lines of advance.

It has been realised for some time that there were many examples of combination differences between the frequencies of the γ-rays from any one body, and that this indicated, what was otherwise probable, that the γ-rays could be associated with a nuclear level system. Little progress, however, was made with this idea for several years, due to the realisation of the difficulty of associating such a level system with any specific part of the nucleus. In the nucleus there are α-particles, protons, and electrons, and in general any of these particles might be the emitters of the γ-rays. This question is still open, but there is now sufficient evidence to make it reasonable to try the hypothesis that the γ-rays are emitted by transitions of α-particles between stationary states in the nucleus.

The theories of Gamow and of Gurney and Condon [6] have shown that we may regard the process of emissions of an α-particle as due to the gradual leak of the wave function through a potential barrier. An extremely important result of this view is that the energy of the α-particle outside the atom, which can of course be measured, is the same as the energy of the α-particle in the stationary state in the nucleus which it occupied before the disintegration. For example, the α-particle from radium C is found to be emitted with an energy of 7·68 million volts. We therefore deduce that in the radium C nucleus there is an α-particle level with a positive energy of this amount. Such a level gives a natural basis on which to build the level system deducible from the γ-rays. We imagine that as a result of some internal nuclear arrangement an α-particle is excited to one of certain higher states, and that from these states it arrives at the ground state by emitting γ-rays of frequencies corresponding to the energy differences. It now follows, however, that if an α-particle can leak out through the potential barrier from the ground level, it can do so still more easily from the excited levels. We should therefore expect to find a certain number of high-speed α-particles corresponding to these modes of disintegration.

The existence of such long-range α-particles has of course been known for a long time, and in fact many tentative suggestions have been put forward associating the energy differences of the groups of α-particles with the frequencies of the γ-rays. The present-day point of view, however, goes much further than this, since it predicts definite relations between the intensities of the γ-rays and the number of long-range particles. That such a relation must exist can be easily seen in the following way. Suppose that on the average out of every thousand disintegrations there are n cases where an α-particle is excited to a certain state, the rate of leak through the potential barrier is given to a fair approximation by theory, and the probability of the nuclear transition can at least be estimated. We are therefore able in terms involving only the unknown quantity n to write down the number of long-range α-particles we should expect and the number of quanta of radiation. Both these quantities can also be measured, perhaps not with a very high accuracy, but yet sufficient to see whether there is an agreement with theory or not.

This is really a stringent test for the theory, because although the theories of the probabilities of nuclear transitions are necessarily tentative, any adjustment which proved necessary for one γ-ray must also apply to all the others. By arguments of this type Fowler [7] has been led to associate one excited α-particle level of the radium C nucleus with the corresponding nuclear transition formed from the β-ray spectrum. It seems likely that this line of investigation will lead to definite and valuable results. It is of course quite probable that several nuclear transitions will not be able to be associated with long-range α-particles, but it would then be possible to draw the important conclusion that these transitions were due to protons or α-particles of small positive or of negative energy.

Internal Conversion.

Reference was made above to internal conversion and it was pointed out that groups of electrons are ejected from the K, L, M states of radioactive atoms with just those energies that they would have if radiation were emitted from the nucleus but was absorbed photoelectrically before it escaped.

It has been frequently pointed out that there was no need and, in fact, no justification to assume that in this case the radiation was ever actually emitted at all.[8] All that could be truly inferred from the experimental results was that an excited nucleus could either emit its excess energy as radiation or had some means of transferring this energy to the electronic structure of the atom.

On the old quantum mechanics, it was difficult to imagine any method other than that of radiation transfer, but the wave mechanics suggests that there is a far more intimate connexion between the nuclear particles and the electronic structure. The wave functions of the particles in the nucleus will extend out to a certain extent into the electronic region of the atom, and conversely the electronic wave functions will exist throughout the nucleus. As a model, we may think that every electron in the atom occasionally passes right through the nucleus, and that a nuclear particle might sometimes for a very short time be found to be actually outside the nucleus.

We have thus no difficulty in seeing, in a general way, how the nuclear energy might be transferred to the electronic system by a direct collision process. Which process, radiation or collision, is predominant can only be settled by experiment, and the answer given by experiment in this case is fortunately unambiguous. The measurements of Ellis and Aston [5] of the extent of this internal conversion and of the way in which it depends on the frequency of the associated radiation show clearly that the behaviour is incompatible with the radiation hypothesis, and we are thus led to conclude that the collision process is the most important. It will be seen that this process is really a collision of the second kind, between an electron and an excited nucleus.

The peculiar interest of this phenomenon lies in the fact that it represents an easily measurable example of direct interaction between the nucleus and the electronic system. There are several other cases where the interaction between the nucleus and the electronic system must be taken into account, but only in order to give the finer details. The importance of the phenomenon of internal conversion is that the entire phenomenon, even to its first approximation, depends upon interaction, and that no approach can be made to it with a simple point nucleus.

However, quite apart from the intrinsic interest of this interaction, the phenomenon of internal conversion seems likely to provide valuable information about the stationary states in the nucleus. The quantity that can actually be measured, the internal conversion coefficient, is the ratio of the probabilities of occurrence of this collision of the second kind and of the nuclear radiation transition. The latter is determined mainly by the energy difference of the initial and final states, whilst the absolute energies are involved in the former. In a general way it can be seen that the internal conversion should lead to a classification of the levels responsible for the γ-rays, or, in other words, should enable the γ-rays to be associated with a definite part of the nucleus.

While but little has yet been accomplished along these various lines of investigation of the nuclear levels, it is certainly true that the most difficult step has already been made. The problem can now be clearly envisaged, and definite lines of work proposed which seem likely to lead to results. The way appears open to an experimental investigation of certain radioactive nuclei, and to an interpretation of the experimental results in terms of nuclear phenomena.

[1] Rutherford and Andrade, *Phil. Mag.*, **27**, 854 ; **28**, 262 ; 1924. Thibaud, Thèse, Paris, 1925. Frilly, Thèse, Paris, 1928. Meitner, *Zeit. f. Physik*, **52**, 645 ; 1928.
[2] Steadman, *Phys. Rev.*, **36**, 460 ; 1930.
[3] Ellis, *Proc. Roy. Soc.*, A, **101**, 1 ; 1922. Thibaud, Thèse, Paris, 1925.
[4] Skobeltzyn, *Zeit. f. Physik.*, **43**, 354 ; 1927 : **58**, 595 ; 1929.
[5] Ellis and Aston, *Proc. Roy. Soc.*, A, **129**, 180 ; 1930.
[6] Gamow, *Zeit. f. Physik*, **51**, 204 ; 1928. Gurney and Condon, NATURE, **122**, 439 ; 1928.
[7] Fowler, *Proc. Roy. Soc.*, A, **129**, 1 ; 1930.
[8] Smekal, *Zeit. f. Physik*, **10**, 275 ; 1922. *Ann. d. Phys.*, **81**, 399 ; 1926. Rosseland, *Zeit. f. Physik*, **14**, 173 ; 1923.

An Institute for Experimental Research in Surgery.

THANKS to the munificence of Mr. George Buckston Browne, the Council of the Royal College of Surgeons of England will be able to build, equip, and maintain an Institute for Experimental Research in Surgery, to be known by the donor's name. For the building and maintenance of such an Institute, and for the endowment of experimental research, Mr. Buckston Browne has given £50,000, with a promise to make further additions until a total of £100,000 is reached.

This munificent gift will give England what she now lacks—an institute where surgeons can carry out experimental research bearing on their art. The Institute is part of a scheme which was initiated by the Council of the College of Surgeons some years ago, when it equipped laboratories for surgical research in connexion with the Museum in Lincoln's Inn Fields. The workers now engaged in these laboratories have found that their investigations are crippled by the lack of a biological station or farm in the country where experimental animals can be maintained and observed under the best conditions. Mr. Buckston Browne's generosity makes the completion of the Council's scheme now possible.

It will be remembered that three years ago Mr. Buckston Browne acquired Down House, Kent, from Prof. C. G. Darwin, F.R.S., and after restoring and endowing it, presented it to the British Association to be preserved as a memorial to Darwin, and for such scientific purposes as the Council of the Association might determine. It was Mr. Buckston Browne's original intention to establish the Institute which is to bear his name on the grounds attached to Down House ; but certain circumstances compelled an alteration of this plan. The chief of these was that the land lying to the west of the Down property and flanking