it is at least satisfactory to find that attention is being paid to things which are involved in such baffling perplexity that the easiest course is to look the difficulty steadily in the face and pass by. When the investigator emerges who is able and willing to tackle the problem, he must not be afraid of finding results which his present knowledge may lead him to think as absurd as the properties of radium seemed before they were discovered.

In the course of correspondence in the *Times*, induced by the article on dowzers and doubters already referred to, Mr. A. A. Campbell Swinton outlined in the issue of Nov. 30 a scheme of in-

vestigation which he suggested might be taken up by the National Physical Laboratory. He proposes the construction of an underground channel through which a controlled supply of water might be allowed to flow or percolate in such a manner that the fact of sensitiveness to the presence of water could be tested and, if found, the rate of transmission of the impulse from the water to the dowser might be measured. If this suggestion were acted upon, a committee, which would satisfy both the credulous and the sceptical, could no doubt be brought together to arrange details of the tests.

The Use of Radio-Elements as Indicators.¹

By Prof. FRITZ PANETH.

THE use of radio-elements as indicators is a special chapter of radioactive investigation, which differs from the topics usually treated under the name of radioactive research, in so far that the radio-elements are here not the object of the study, but are used as a mere agent in the solution of problems which in general have nothing to do with radioactivity at all. These problems may be found in very different branches of chemistry, physics, and even biology, and it is to be expected that radio-elements as indicators will be more used the more familiar the advantages of this method become to non-radiologists.

Only an elementary knowledge of the principles of radioactivity is necessary in order to understand and even to apply the method. It is based upon the extreme sensitivity of radioactive measurements, and upon the chemical relations of the radio-elements to ordinary elements.

As to the first point, it is well known that by help of an electroscope, invisible and imponderable quantities of radioactive matter can be detected and exactly measured. From the radio-element thorium *C*, for example, which can very frequently be used as an indicator, 10^{-17} gm. allows for exact qualitative and quantitative determination. Now thorium *C* is 'isotopic' with ordinary bismuth. Since isotopes show identical chemical properties, it is possible to substitute the radio-element for its inactive isotope, and to acquire information concerning the element in extremely dilute solutions. The chemical behaviour of bismuth may thus be elucidated by a study of thorium *C*. In certain cases it is found advantageous to mix a certain amount of the radio-element with a sample of the inactive element in order that an otherwise indeterminable fraction of the original quantity may be detected or determined electroscoically. Instances in which such minute fractions of an element have been separated by some such process as diffusion, solution, or volatilisation, are discussed below. By choice of

the appropriate ratio between the quantities of inactive element and radio-element in the sample, it is possible to cover the entire range of mixtures from those detectable only by means of the electroscope to those containing readily weighable amounts of material.

In selecting a radio-element for use as an indicator, it is generally desirable to find one that may be detected in very small amounts. It must be borne in mind, however, that the half-value period (*T*) varies inversely with the intensity of radiation, and that an element detectable in small quantities invariably has a short half-value period. It would therefore never be feasible to employ radium *C'* (*T* = 10^{-7} seconds) or thorium *C'* (*T* = 10^{-11} seconds) as indicators. Even the three indicators available for the element thallium are too short-lived for a number of experiments.

For this reason it is not practicable to use all of the elements included in the well-known lists of radioactive isotopes for the present purpose. Only the elements named in the following table can find practical application. Those to be recommended most highly are underlined in the table.

Even radio-elements such as ionium, uranium *X*₁, and uranium *X*₂, which possess no inactive isotopes, frequently are of service in increasing the radioactive intensity of their longer-lived, less active, and therefore less readily detectable radioactive isotopes. Uranium *X*₁, for example, is mentioned in the table as a satisfactory indicator for thorium. So also, thorium *X* may be used as indicator for radium, and radium *A* for polonium. But radium and polonium themselves may in a broader way be employed as indicators in certain lines of work. For, in the narrower sense, the function of the radio-elements 'as indicators' may be conceived to be restricted to those experiments in which the radio-elements are substituted for their active or inactive isotopes. In the broader sense, however, this function may be extended to cover any procedure in which the radio-element is used as an instrument in the detection, determination, or investigation of matter in minute quantities.

A brief account of some examples, where radio-

¹ From an address delivered to the Bedson Club, Newcastle-upon-Tyne, on Mar. 17, 1927. A fuller discussion of the subject in English by the same author, with references to the literature, will shortly appear in Volume 2 of the Baker Lectures, delivered by non-resident lecturers at Cornell University (Ithaca, N.Y.). For literature, see also G. Hevesy and F. Paneth, "Manual of Radioactivity" (Oxford, 1926).

elements have actually been used with success as indicators—rather than an abstract discussion of possible applications of this method—may help to a fuller understanding.

From the large number of experiments with radio-elements as indicators in the field of analytical chemistry, the choice of one typical case may well suffice. The solubility of lead chromate at room temperature is too small to admit of accurate determination by simple gravimetric methods. It is of course possible, in cases of this sort, to make use of conductivity measurements, or to calculate the solubility product from the equilibrium constants. With concentrations as low as that of the

the saturated solution of this compound has been held at the desired temperature in a thermostat for a sufficient time, its composition may be ascertained by evaporating a few cubic centimetres to dryness, and measuring the activity of the well-nigh invisible residue in the electroscope. (This example is treated in more detail because the general procedure is typical also of the following cases.)

Had the radio-elements been available for use as indicators during the last quarter of the nineteenth century, one extremely important service might have been rendered with their aid, to the then newly advanced theory of *electrolytic dissociation*. Proof of the actual fact of dissociation, and of the interchange of ions, is readily obtainable with the help of the radio-elements, mixed, in accordance with the procedure just outlined, with their inactive isotopes. It is possible to demonstrate in this way the fact that the particular atoms or radicals assumed to be liberated by electrolytic dissociation do not retain their places in given molecules, but are free to move back and forth from one place to another. If, for example, equimolecular amounts of an inactive lead chloride and a radiochemically sensitised lead nitrate in aqueous solutions are mixed together, and the lead chloride is allowed to crystallise again, it will be found that the active lead atoms are distributed proportionally between chloride and nitrate, and must therefore have migrated in solution from lead nitrate to lead chloride until the kinetic equilibrium has been established.

Radio-elements have further shown their utility in connexion with *measurements of the surface of powdered adsorbents*. Information concerning the extent of surface is obviously necessary in deciding whether the adsorbed layer is of the thickness of one, or of more than one molecule. This question has been answered in various ways by various theories of adsorption. Particularly in the case of powders, which, because of their greatly extended surface, are preferentially used as adsorbents, determinations of superficial magnitudes have hitherto been unsuccessful. If the choice of materials be limited, however, to solid compounds of elements possessing a known radioactive isotope, a safe and simple method becomes available. It is based upon the fact that the radio-element, added to the saturated solution of the isotopic adsorbent, becomes in a very short time equally distributed between the molecules of the dissolved part of the adsorbent and those of the uppermost layer of its crystalline surface. In this way the extent of the surface can easily be computed from the decrease of the radioactivity of the solution. The surface of the sulphate and sulphide of lead, of the phosphate of bismuth, and so on, have thus been measured, and with these values it has been able to establish the fact that on all these adsorbents the limit of adsorption is reached as soon as a layer of one molecule in thickness has been formed.

From the chemistry of inorganic preparations, the discovery of the *volatile hydride of bismuth*

RADIOACTIVE INDICATORS.

Element.	Indicator.
Thallium	Radium <i>C''</i> $T = 1.32\ m$ Thorium <i>C''</i> $3.20\ m$ Actinium <i>C''</i> $4.76\ m$
Lead	Radium <i>B</i> $26.8\ m$ Radium <i>D</i> $16.0\ y$ Thorium <i>B</i> $10.6\ h$ Actinium <i>B</i> $36.0\ m$
Bismuth	Radium <i>C</i> $19.5\ m$ Radium <i>E</i> $4.85\ d$ Thorium <i>C</i> $60.5\ m$ Actinium <i>C</i> $2.16\ m$
Polonium $T = 136\ d$	Radium <i>A</i> $3.05\ m$
Radon $3.85\ d$	Thoron $54.5\ s$ Actinon $3.92\ s$
Radium $1580\ y$	Thorium <i>X</i> $3.64\ d$ Actinium <i>X</i> $11.2\ d$
Actinium $20\ y$	Mesothorium 2 $6.13\ h$
Thorium $1.65 \times 10^{10}\ y$	Ionium $7.6 \times 10^4\ y$ Radiothorium $1.90\ y$ Radioactinium $18.9\ d$ Uran. <i>X</i> ₁ $23.9\ d$
Protactinium $1.2 \times 10^4\ y$	Uran. <i>X</i> ₂ $1.17\ m$

saturated solution of lead chromate, however, either of these methods would entail a lengthy and delicate investigation. With the aid of a radioactive indicator, on the other hand, the solubility of lead chromate may be measured with no more difficulty than that involved in a simple weighing.

To a definite amount of a soluble lead salt, a known quantity of thorium *B* is added. The activity of this preparation may be measured in any desired units, as, for example, the number of scale divisions per minute on the particular electroscope used. If, for example, 10,000 units of thorium *B* is thoroughly mixed with 10 milligrams of lead, it is apparent that one unit of thorium *B* will invariably indicate the presence of 0.001 milligram of lead. From the artificially activated lead thus obtained it is now possible by the usual chemical methods to prepare the chromate. After

with the help of its isotopic radio-elements may be mentioned. From many fruitless investigations it had to be concluded that this compound, if it could be prepared, would be obtained only in very minute fractions of the initial material, and might therefore easily escape detection by the usual methods of analysis. The apparatus for measuring radioactivity can, however, be selected so that a ten-millionth part of the bismuth in the original material will give a product recognisable with certainty, both qualitatively and quantitatively. This wide extension of the range of measurement is quite necessary if the condensation and re-volatilisation of bismuth hydride are to be detected; its mere existence can be proven by relatively simple means and even by a lecture experiment. Decomposition of magnesia turnings, covered with thorium *C* or radium *C*, by dilute hydrochloric acid, yields the volatile hydrides of these radio-elements, which can be condensed at the temperature of liquid air and—on the other hand—decomposed and measured in a heated glass-tube. After experience had been gained with the radioactive method described above in the study of the best method of preparation, and of the stability of bismuth hydride, it was found possible later, with comparatively little difficulty, to prepare this compound also from inactive bismuth, making use of magnesium as before in the preparation of the hydride. It may be mentioned that the amount of material by which the existence of the compound was first recognised was but 10^{-16} gram, and that it was found possible, with further increase in the sensitivity of the process of detection, to establish by the use of radioactive indicators the existence of a *gaseous lead hydride* formed in still smaller amounts. Here also the radioactive test was a spur to ultimately successful experiments with ordinary lead.

That radioactive indicators might occasionally serve to advantage in *technological research* can scarcely be doubted, even if they have been more frequently applied hitherto to scientific problems. A question of this type is that of testing rubberised fabrics for their permeability to gases. When, during the War, in connexion with the choice of suitable samples of material for gas masks, the task of determining numerically the permeability to gases of the materials submitted by different firms was assigned, it was found convenient to employ, as a test gas, air with which was mixed a trace of radium emanation (radon). The fractional portion of the gas which penetrated the material under investigation could then be determined electroscopically.

A considerable number of problems in physics can be brought to solution through the agency of radioactive indicators. Among these, the experimental study of '*self-diffusion*' is of paramount importance. By this is understood the phenomenon, expected from the kinetic theory of matter, that the atoms of a homogeneous gaseous or liquid element move among one another under the same law that applies in the case of a diffusion of one element into another. Since in self-diffusion, how-

ever, the external properties of the element in question remain entirely unchanged, it has been possible to carry out this process hitherto only as an imaginary experiment, of which indeed Maxwell and Boltzmann have made frequent use. G. Hevesy, the author of many experiments with radioactive indicators, has succeeded in bringing self-diffusion within the scope of observation. He prepared and sealed in a hard glass tube, a fused cylinder of lead, of which three-fourths was ordinary lead and one-fourth activated lead; thorium *B* was used as radioactive indicator in experiments of only short duration, while the long-lived radium *D* was chosen for more extended experiments. If now the lead in the tube is cautiously melted, and is held at this temperature for several days, it is easy, after solidification, to measure the distribution of the activity that has taken place within the lead column during the period of the experiment. In this case, therefore, marked lead atoms have diffused among other lead atoms, and the self-diffusion constant can be calculated by the usual methods.

Among other applications to physical research which can only be mentioned here, are the formation of various alloys at low temperatures, the speed of solution of very thin layers, the rate of evaporation in relation to the amount of liquid to be evaporated, and diffusion in ideally dilute solutions.

Since bismuth compounds of very diverse composition have recently been investigated from the viewpoint of therapeutics as a substitute for arsenic, it was of interest to physiologists to learn in what proportions the *bismuth* introduced is *stored up in the different organs of the body*, and is eliminated in the urine and faeces. Since small amounts only are involved, the determination can best be accomplished by the radioactive method. Radium *E* was employed as indicator for bismuth in place of thorium *C*, in view of the fact that the experiments extended over a period of several days. It was mixed with the bismuth preparations and injected intra-muscularly into the guinea-pigs employed in the experiments. The products of excretion were ashed and measured electroscopically, and after the end of the experiment the organs of the animals were similarly treated. One conclusion to be drawn from the chart showing the exact distribution of the bismuth, is that the accumulation of this element takes place chiefly in the kidneys. Analogous experiments with lead preparations show that absorption takes place chiefly in the liver. The absorption and distribution of lead in roots, leaves, and fruits of a plant (*Vicia faba*) were investigated in a similar way.

The examples of the use of radio-elements as indicators here presented may suffice to show that the method thus illustrated is capable of many-sided application. It is to be hoped that in the future a greater number of chemists and physicists than heretofore may make use of the method, and may thereby facilitate materially the solution of many problems.