the volume obtained from the radium to be 0.1 cubic mm. This corresponds to a rate of production of helium per gram of radium per year of about 20 cubic mms. This is only about one fifth of the theoretical amount calculated above. Ramsay and Soddy do not lay much stress on the accuracy of their estimate, as they consider that the presence of a trace of argon may have seriously interfered with the correctness of the estimate by the spectroscopic method. An accurate measurement of the rate of production of helium by radium would be of the utmost value at the present time in settling the connection between the α particle and helium.

If the α particle is a helium atom, the greater proportion of the α particles expelled from the emanation enclosed in a small tube will be projected into the glass envelope. The swiftest moving particles, viz., those expelled from radium C, would probably penetrate the glass to a depth of about 1/20 of a millimetre, while the slower moving particles would be stopped after traversing a somewhat shorter distance.

It has already been pointed out (page 88) that this may explain why the volume of the emanation in the first experiment by Ramsay and Soddy shrank almost to zero. The helium in this case was retained in the glass. In the second experiment the helium may have diffused from the glass tube into the gas again. Ramsay and Soddy endeavored to settle this point by testing whether helium was released by heating a glass tube in which the emanation had been enclosed for several days and then removed. The spectroscope momentarily showed some of the helium lines, but these were soon obscured by the presence of other gases liberated by the heating of the tube.

Age of Radioactive Minerals

The helium observed in the radioactive minerals is almost certainly due to its production from the radium and other radioactive substances contained therein. If the rate of production of helium from known weights of the different radio-elements were experimentally known, it should thus be possible to determine the interval required for the production of the

amount of helium observed in radioactive minerals, or, in other words, to determine the age of the mineral. This deduction is based on the assumption that some of the denser and more compact of the radioactive minerals are able to retain indefinitely a large proportion of the helium imprisoned in their mass. In many cases the minerals are not compact but porous, and under such conditions most of the helium will escape from its mass. Even supposing that some of the helium has been lost from the denser minerals, we should be able to fix with some certainty a minimum limit for the age of the mineral.

In the absence of definite experimental data on the rates of production of helium by the different radioelements, the deductions are of necessity somewhat uncertain, but will nevertheless serve to fix the probable order of the ages of the radioactive minerals.

It has already been pointed out that all the α particles expelled from radium have the same mass. In addition it has been experimentally found that the α particle from thorium B has the same mass as the α particle from radium. This would suggest that the α particles projected from all radioactive substances have the same mass, and thus consist of the same kind of matter. If the α particle is a helium atom, the amount of helium produced per year by a known quantity of radioactive matter can readily be deduced on these assumptions.

The number of products which expel α particles are now well known for radium, thorium, and actinium. Including radium F, radium has five α ray products, thorium five, and actinium four. With regard to uranium itself, there is not the same certainty, for only one product, UrX, which emits only β rays, has so far been chemically isolated from uranium. The α particles apparently are emitted by the element uranium itself; at the same time, there is some indirect evidence in support of the view that uranium contains three α ray products. For the purpose of calculation, we shall, however, assume that in uranium and radium in equilibrium, one α particle is expelled from the uranium for five from the radium.

Let us now consider an old uranium mineral which contains one gram of uranium, and which has not allowed any of the

products of its decomposition to escape. The uranium and radium are in radioactive equilibrium and 3.8×10^{-7} grams of radium are present. For one α particle emitted by the uranium, five are emitted by the radium and its products, including radium F. Now we have shown that radium with its four α ray products probably produces .11 c.c. of helium per gram per year. The rate of production of helium by the uranium and radium in the mineral will consequently be $\frac{5}{4} \times .11 \times 3.8 \times 10^{-7} = 5.2 \times 10^{-8}$ c.c. per year per gram of uranium.

Now, as an example of the method of calculation, let us consider the mineral fergusonite which was found by Ramsay and Travers to evolve 1.81 c.c. of helium per gram. The fergusonite contains about 7 per cent of uranium. The amount of helium contained in the mineral per gram of uranium is consequently 26 c.c.

Since the rate of production of helium per gram of uranium and its radium products is 5.2×10^{-8} c.c. per year, the age of the mineral must be at least $26 \div 5.2 \times 10^{-8}$ years or 500 million years. This, as we have pointed out, is a minimum estimate, for some of the helium has probably escaped.

We have assumed in this calculation that the amount of uranium and radium present in the mineral remains sensibly constant over this interval. This is approximately the case, for the parent element uranium probably requires about 1000 million years to be half transformed.

As another example, let us take a uranium mineral obtained from Glastonbury, Connecticut, which was analyzed by Hillebrande. This mineral was very compact and of high density, 9.62. It contained 76 per cent of uranium and 2.41 per cent of nitrogen. This nitrogen was almost certainly helium, and dividing by seven to reduce to helium this gives the percentage of helium as 0.344. This corresponds to 19 c.c. of helium per gram of the mineral, or 25 c.c. per gram of uranium in the mineral. Using the same data as before, the age of the mineral must be certainly not less than 500 million years. Some of the uranium and thorium minerals do not contain much helium. Some are porous, and must allow the helium to escape readily.

A considerable quantity of helium is, however, nearly always found in the compact primary radioactive minerals, which from geologic data are undoubtedly of great antiquity.

Hillebrande made a very extensive analysis of a number of samples of minerals from Norway, North Carolina, and Connecticut, which were mostly compact primary minerals, and noted that a striking relation existed between the proportion of uranium and of nitrogen (helium) that they contained. This relation is referred to in the following words: —

"Throughout the whole list of analyses in which nitrogen (helium) has been estimated, the most striking feature is the apparent relation between it and the UO_2. This is especially marked in the table of Norwegian uraninites, recalculated from which the rule might almost be formulated that, given either nitrogen or UO_2, the other can be found by simple calculation. The same ratio is not found in the Connecticut varieties, but if the determination of nitrogen in the Branchville mineral is to be depended on, the rule still holds that the higher the UO_2 the higher likewise is the nitrogen. The Colorado and North Carolina minerals are exceptions, but it should be borne in mind that the former is amorphous, like the Bohemian, and possesses the further similarity of containing no thoria, although zirconia may take its place, and the North Carolina mineral is so much altered that its original condition is unknown."

Very little helium, however, is found in the secondary radioactive minerals, *i. e.*, minerals which have been formed as a result of the decomposition of the primary minerals. These minerals, as Boltwood has pointed out, are undoubtedly in many cases of far more recent formation than the primary minerals, and consequently it is not to be expected that they should contain as much helium. One of the most interesting deposits of a secondary uraninite is found at Joachimsthal in Bohemia, from which most of our present supply of radium has been obtained. This is rich in uranium, but contains very little helium.

When the data required for these calculations are known with more definiteness, the presence of helium in radioactive minerals will in special cases prove a most valuable method of computing

their probable age, and indirectly the probable age of the geological deposits in which the minerals are found. Indeed, it appears probable that it will prove one of the most reliable methods of determining the age of the various geological formations.

Significance of the Presence of Lead in Radioactive Minerals

If the α particle is a helium atom, the atomic weights of the successive α ray products of radium must differ by equal steps of four units. Now we have seen that uranium itself probably contains three α ray products. Since the atomic weight of uranium is 238.5, the atomic weight of the residue of the uranium after the expulsion of three α particles would be $238.5 - 12, = 226.5$. This is very close to the atomic weight of radium 225, which we have seen is produced from uranium. Now radium emits five α ray products altogether, and the atomic weight of the end product of radium should be $238.5 - 32, = 206.5$. This is very close to the atomic weight of lead, 206.9. This calculation suggests that lead may prove to be the final product of the decomposition of radium, and this suggestion is strongly supported by the observed fact that lead is always found associated with the radioactive minerals, and especially in those primary minerals which are rich in uranium.

The possible significance of the presence of lead in radioactive minerals was first noted by Boltwood,[1] who has collected a large amount of data bearing on this question.

The following table shows the collected results of an analysis of different primary minerals made by Hillebrande: —

Locality.	Percentage of uranium.	Percentage of lead.	Percentage of nitrogen.
Glastonbury, Connecticut	70–72	3.07–3.26	2.41
Branchville, Connecticut	74–75	4.35	2.63
North Carolina	77	4.20–4.53	
Norway	56–66	7.62–13.87	1.03–1.28
Canada	65	10.49	0.86

[1] Boltwood: Phil. Mag., April, 1905; Amer. Journ. Science, Oct., 1905.

Five samples were taken of the minerals from Glastonbury, three from Branchville, two from North Carolina, seven from Norway, and one from Canada. In minerals obtained from the same locality, there is a comparatively close agreement between the amounts of lead contained in them. If helium and lead are both products of the decomposition of the uranium radium minerals, there should exist a constant ratio between the percentage of lead and helium in the minerals. The percentage of helium is obtained from the above table by dividing the nitrogen percentage by seven. Since probably eight α particles are emitted from the decomposition of uranium and radium for the production of one atom of lead, the weight of helium formed should be $\frac{8 \times 4}{206.9} = .155$ of the weight of lead. This is based on the assumption that all the helium formed is imprisoned in the minerals. The ratio actually found is about .11 for the Glastonbury minerals, .09 for the Branchville minerals, and about .016 for the Norway minerals. It will be noted that in all cases the ratio of helium to lead is less than the theoretical ratio, indicating that in some cases a large proportion of the helium formed in the mineral has escaped. In the case of the Glastonbury minerals, the observed ratio is in good agreement with theory.

If the production of lead from radium is well established, the percentage of lead in radioactive minerals should be a far more accurate method of deducing the age of the mineral than the calculation based on the volume of helium, for the lead formed in a compact mineral has no possibility of escape.

While the above considerations are of necessity somewhat conjectural in the present state of our knowledge, they are of value as indicating the possible methods of attacking the question as to the final products of the decomposition of the radioactive minerals. From a study of the data of analyses of radioactive minerals, Boltwood has suggested that argon, hydrogen, bismuth, and some of the rare earths possibly owe their origin to the transformation of the primary radioactive substances.

It does not appear likely that we shall be able for many years

to prove or disprove experimentally that lead is the final product of radium. In the first place, it is difficult for the experimenter to obtain sufficient radium for working material, and, in the second place, the presence of the slowly transformed product radium D makes a long interval necessary before lead will appear in appreciable quantity in the radium. A more suitable substance with which to attack the question would be radium F (radiotellurium) or radiolead (radium D).

Constitution of the Radioelements

The view that the α particle is a helium atom suggests that the atoms of uranium and radium are built up in part of atoms of helium. If the final product of radium is lead, the radium atom could thus be represented by the equation, $Ra = Pb \cdot He_5$, while $Ur = Pb \cdot He_8$.

It must be borne in mind, however, that these compounds of helium are very different from ordinary molecular compounds. Both radium and uranium behave as elementary substances, which cannot be broken up by the application of physical or chemical forces at our command. These substances spontaneously break up at a rate that is independent of known agencies, and the disintegration is accompanied by the expulsion of a helium atom with enormous velocity. The energy liberated in the form of the kinetic energy of the expelled helium atoms is of quite a different order from that observed in molecular reactions, being at least one million times as great as that released in the most violent chemical combinations. It seems probable that the helium atoms are in very rapid motion within the atoms of uranium and radium, and for some reason escape from the atoms with the velocities which they possessed in their orbits. The forces that hold the helium atoms in place in the atom of the radioelements are so strong that no means at our disposal are able to effect their separation.

It seems probable that the α particles from thorium and actinium are also helium atoms, so that these substances must also be considered as compounds of some unknown substances with