Since it has been shown by Alexopoulos[11] and Oliphant and Westcott[12] that no gamma-rays accompany the disintegration at the voltages used in this experiment, the variation in range with angle makes it appear that at these voltages, if $_4Be^8$ is formed and subsequently disintegrates into two 8.4-cm alpha-particles without the emission of a gamma-ray, it must have a mean life of not more than $3 \cdot 10^{-14}$ second.

The ranges calculated for a thick target at these voltages show no experimentally observable deviation from those for a thin target except in the extreme forward direction where the difference is observable and the observed range agrees with that calculated for the thick target. This agreement gives a separate additional check on the conservation of momentum, and, assuming that the theoretical data of Mano for the proton energy-range relation are correct, gives an approximate verification of the shape of the yield curves obtained by Herb, Parkinson and Kerst.[8] It must be noted, however, that the predicted mean range is not very sensitive to the shape of the yield curve, and a factor of 1.5 would not affect the calculations enough for the difference to exceed the experimental error.

We wish to acknowledge the valuable assistance of Drs. Giarratana and Brennecke in the construction of the apparatus used in this experiment.

[11] Alexopoulos, Zeits. f. Physik **98**, 336 (1935).
[12] Oliphant and Westcott, London Conf. Rep. I, p. 152.
[13] Rutherford, Wynn-Williams, Lewis and Bowden, Proc. Roy. Soc. **A139**, 617 (1933).

JUNE 1, 1936 PHYSICAL REVIEW VOLUME 49

The Transmutation of Platinum by Deuterons

J. M. CORK AND E. O. LAWRENCE, *Radiation Laboratory, Department of Physics, University of California*

(Received April 7, 1936)

The radioactivity induced in platinum by 5 MV deuterons is composite in character. Chemical separations of the active elements together with an analysis of the decay curves establish that at least two radioactive isotopes each of iridium and platinum are formed. The decay periods of the former are about 28 min. and 8.5 hrs. while the latter have periods in the neighborhood of 49 min. and 14.5 hrs. Inasmuch as the platinum activity emits both positrons and electrons it seems reasonable to ascribe the activities to the isotopes Pt^{193} and Pt^{197} resulting from neutron capture. The active iridium isotopes are probably formed in reactions involving deuteron capture and alpha-particle emission, and the likely radioactive isotopes are Ir^{194} and Ir^{196}. The transmutation functions for the reactions leading to iridium isotopes exhibit maxima indicative of resonance penetration of the platinum nucleus by the deuteron; the nature of the transmutation functions for the reactions giving platinum isotopes is not made certain by these experiments, because of the relative weakness of the platinum activities.

INTRODUCTION

ONE of the noteworthy results of investigations of artificial radioactivity induced by deuterons is that these nuclear reactions can be observed much farther up the periodic table than was expected on the basis of penetration of charged particles through nuclear barriers according to the theories of Gurney and Condon and Gamow. The theory of Oppenheimer and Phillips adequately accounts for the observations of reactions in which only the neutron of the deuteron enters the nucleus, but in the cases of some heavy elements investigated in our laboratory recently, the observations were not even in accord with this theory. Almost every heavy element that was bombarded with 5 MV deuterons exhibited evidences of induced radioactivity characteristic of the element. The yields of radioactivity, however, were small in comparison to those of lighter elements and accordingly the observations were suspected as being due possibly to contaminations.

Platinum, which was one of the heavy elements showing relatively strong radioactivity under deuteron bombardment, was selected for careful study as its chemical and physical proper-

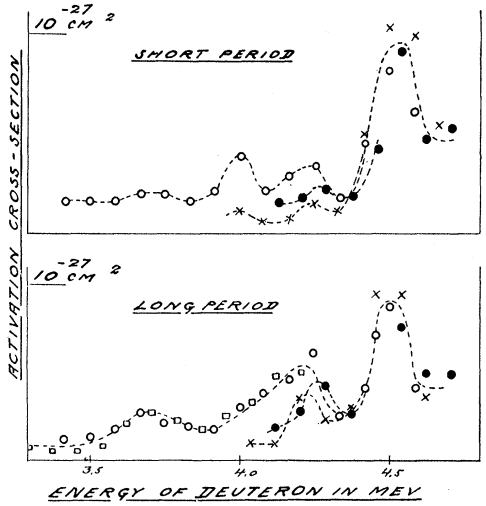

FIG. 1. Transmutation functions (energy-activation curves). Platinum.

ties are favorable to the reduction of contaminants to a minimum. The results of the investigation here reported show definitely that platinum is disintegrated by deuterons of less than 5 MV energy and that the nuclear reactions are understandable in part as an example of resonance penetration of the deuteron into the platinum nucleus.

THE TRANSMUTATION FUNCTION

Preliminary chemical tests[1] indicated that the radioactive substance induced in platinum by deuterons was a noble metal and therefore that in all probability the observed effects were not ascribable to contaminations. It was of immediate interest therefore to determine the transmutation function (the variation with energy of bombarding particle of the probability of the nuclear reaction) for the reaction involved, as it was not clear that platinum should be penetrated to an appreciable extent by such low energy deuterons. The transmutation function was accordingly determined in the same way as in earlier investigations of lighter elements. Stacks of thin platinum foils (thickness 0.000035 inch, stopping power equivalent to 0.45 cm of air) were placed in the beam of deuterons emerging from the magnetic resonance accelerator through a platinum window. The foils were known to be more than 99.9 percent pure platinum and much care was exercised in cleaning them individually. They were rinsed in various solvents including dilute aquaregia and heated to incandescence in a hydrogen flame. That the foils were practically clean was indicated by the consistency of the several sets of observations.

Preliminary experiments indicated that the induced radioactivity was of a complex character with at least two periods, a long period of about 10 hours and a short period of less than an hour. Accordingly the stacks of foils were bombarded with 5μA of deuterons having energies of about 5 MV after which the radioactivity in each foil was observed as a function of the time. From the decay curves of the individual foils it was possible to separate the long and short period activities and evaluate the transmutation function for each activity.[2] The stopping power of the individual foils was determined for alpha-particles from polonium, and a correction which according to Mano[3] is suitable to the faster deuterons was included in evaluating the data.

Three sets of observations are shown in Fig. 1 which is a plot of the activity in arbitrary units in the successive foils through which the deuteron beam passed with an energy indicated by the abscissa. It is seen that the yield of activity is not a monotonic function of deuteron energy as in all previously studied cases, but is a function having several maxima and minima. The observations have a natural interpretation as evidence of the resonance penetration of the platinum nucleus by the deuterons. For the short period activity there are in the range investigated resonance levels in the neighborhood of 4.5, 4.2, 4.0 and 3.7 MV while for the long period activity the 4 MV resonance level seems to be absent. In the region between 3 and 3.5 MV the transmutation function was not examined carefully although it was established that deuterons of energy as low as 3 MV produced an appreciable activity in platinum.

[1] J. M. Cork and E. O. Lawrence, Phys. Rev. **49**, 205 (1936).

[2] Since, as we shall see, both the long and short period activities are complex, these transmutation functions refer to a composite activity and cannot be uniquely interpreted in terms of the elementary reactions involved.

[3] G. Mano, J. de phys. et rad. **5**, 628 (1934).

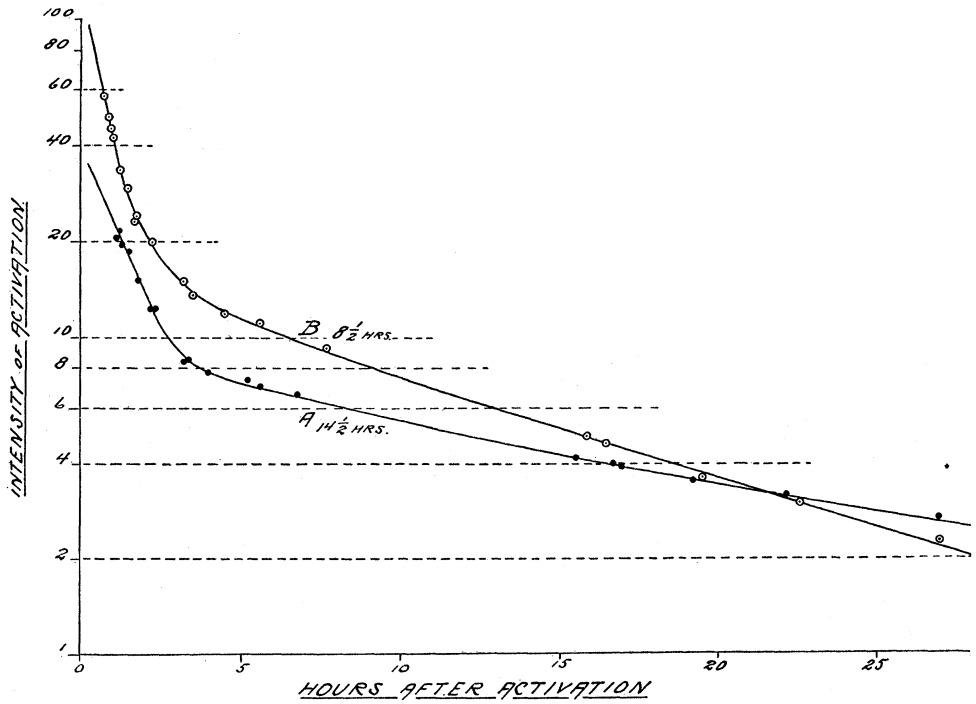

FIG. 2. Decay curves for platinum bombarded by deuterons. Chemical separations. Curve *A*, radio-platinum (49 min.) (14.5 hrs.); curve *B*, radio-platinum (28 min.) (8.5 hrs.).

The order of magnitude of the nuclear activation cross section was obtained from the observation that a platinum foil 3.5×10^{-5} inch thick exposed to 2μA of 4.7 MV deuterons yielded a short period saturation activity of about 10^4 β-particles per sec. This gives for the activation cross section the not unreasonable order of magnitude 10^{-27} cm^2.

Fermi[4] has observed that platinum is rendered weakly radioactive by neutrons. Since we wished to find out whether they played an appreciable role in these experiments, a thick target of platinum was activated by neutrons from a beryllium target bombarded by the deuterons. The neutron intensity from the Be target was about 20 times as great as the neutron radiation from the rest of the accelerator chamber while the activity produced in the thick Pt was less than that produced by the deuteron beam in the individual foils. It was thus clear that the deuterons were reacting directly with the platinum and not through the intermediary of neutrons.

[4] E. Fermi, E. Amaldi, O. d'Agostino, F. Rasetti and E. Segrè, Proc. Roy. Soc. **A146**, 483 (1934).

CHEMICAL IDENTIFICATION OF THE RADIOACTIVE SUBSTANCES

It was clearly important to identify by chemical means the radioactive substances as this would throw essential light on the character of the nuclear reactions involved. Accordingly a careful chemical separation of the substances was made, an account of which follows.[5]

In the chemical analysis of the activated platinum tests were made to make sure that the effects observed were not due to traces of lighter elements. In particular the possibility of traces of the platinum-like elements, rhodium and palladium, was examined carefully since these substances would probably be activated about one hundred times as strongly as platinum. It will be seen that the analysis was carried out in a variety of ways in order to eliminate other possible contaminants. In addition, the operations of the analysis eliminated the possibility that the effect was due to the common surface

[5] We are greatly indebted to Dr. H. W. Newson who very kindly carried through these chemical separations for us.

contaminations, sodium, chlorine, carbon, and oxygen.

In a preliminary experiment an activated platinum foil was dissolved in aquaregia and the platinum was precipitated by reduction with formic acid. Since the precipitated metal carried the radioactivity with it, there was a strong presumption that the active atoms were isotopic with the platinum metals, gold or mercury. An analysis was carried out for all these elements, with the exception of osmium and ruthenium which would distill away as volatile oxides during the solution of the sample in aquaregia. Several active platinum foils were dissolved in aquaregia and small amounts of test solutions of gold, iridium, rhodium, and palladium were added. The analysis was carried out by the method of Noyes and Bray;[6] gold and any mercury present were separated by extraction, platinum and iridium were precipitated together, and finally palladium and rhodium were precipitated separately in the order given. Only the platinum and iridium precipitate showed an appreciable activity so that it is quite definite that the long periods at least are due to isotopes of these elements. The reactions in this case are very nearly unique; the precipitates were $(NH_4)_2PtCl_6$ and $(NH_4)_2IrCl_6$ and because of the rarity of insoluble ammonium salts almost no other elements could be precipitated at this point which would also be precipitated by formic acid. Because of the time required in the analysis, the possibility that the shorter periods were due to rhodium was not eliminated since these periods would have disappeared before the separation was complete. The conditions in the case of palladium which was precipitated next to last were much more favorable, and it is probable that either of the short periods would have been detected if it had been precipitated at this point.

For the final separation a free sample was activated and dissolved, and a small amount of iridium test solution was added. Iridium was precipitated as IrO_2 by the addition of $NaBrO_3$, and platinum was precipitated from the filtrate as $(NH_4)_2PtCl_6$. Both precipitates were found to be active and the activities were observed to decay as shown in Fig. 2. Palladium and rhodium, if present, would precipitate with iridium so that there is a possibility that the short period which precipitated with iridium was due to rhodium. No rhodium period, however, is known to correspond to this half-life so that there is no reason to attribute this period to rhodium.

In order to be sure that the separations were clean, the precipitates were examined after the decay curves had been measured. From the color of the platinum precipitate it was estimated that not more than 0.1 mg of iridium had precipitated with 10 mg of platinum. An analysis of the IrO_2 precipitate showed the presence of about the same percentage of platinum. The separations were, therefore, as complete as could be expected.

In order to be certain that the iridium activity was not due to an iridium impurity in the platinum target, a piece of platinum was covered with a layer of iridium and bombarded. If this activity were due to iridium in the platinum, the contaminated target should give at least one hundred times the activity of the clean platinum target since the platinum did not contain more than 0.2 percent iridium. However, the contaminated target was found to be no more active than the clean target.

Discussion

Thus the evidence is conclusive that the bombardment of platinum by deuterons yields radioactive isotopes of platinum and iridium. Both the platinum and iridium activities are complex, and each element gives a contribution to both long and short period activities. We have thus to account for the formation of at least four radioactive nuclei.

The stable isotopes for this region of the periodic table, as found by Dempster,[7] are shown in the following table where the abundant isotopes are italicized.

76 Os	190		*192*						
97 Ir		*191*		*193*					
78 Pt			192		*194*	*195*	*196*		198
79 Au								*197*	

[6] A. A. Noyes and W. C. Bray, *Analysis for the Rare Elements* (Macmillan, 1927), p. 110. We are indebted to Professor Bray for his suggestions.

[7] A. J. Dempster, Nature **136**, 65, 909 (1935); also **135**, 993 (1935).

Platinum activity

There are clearly three likely radioactive platinum isotopes formed by addition of neutrons, namely, 193, 197 and 199. The first of these would be expected to emit positrons and go over to the iridium isotope of the same mass number, whereas 197 and 199 would be expected to be electron active.

The β-particles emitted from the activated platinum target (containing both radio-iridium and radio-platinum) were observed in the Wilson chamber soon after bombardment, and it was indeed found that about one-fourth of the particles were positrons. The upper energy limit of the positron spectrum is in the neighborhood of 2.1 MV, while that of the electrons is somewhat lower (about 1.7 MV).[8]

Since very soon after bombardment when the short period activities predominate, the platinum activity was about one-fourth that of the iridium, i.e., the same as the ratio of positrons to electrons, it seems probable that the 49 min. platinum activity is to be identified with Pt^{193}, i.e.,

$$_{78}Pt^{192}+{}_{1}H^{2}\rightarrow{}_{78}Pt^{193}+{}_{1}H^{1}$$

$$_{78}Pt^{193}\rightarrow{}_{77}Ir^{193}+{}_{+1}e.$$

Because of the greater abundance of Pt^{196} the 14.5-hr. electron activity of platinum can reasonably be ascribed to Pt^{197}, which decays to gold, i.e.,

$$_{78}Pt^{196}+{}_{1}H^{2}\rightarrow{}_{78}Pt^{197}+{}_{1}H^{1}$$

$$_{78}Pt^{197}\rightarrow{}_{79}Au^{197}+{}_{-1}e.$$

Iridium activity

It is rather more difficult to make tentative identifications of the iridium isotopes because the nuclear reactions in the formation of the radioactive nuclei here involve a decrease by unity of nuclear charge. It is most attractive to assume that these isotopes result from the capture of the deuteron and emission of an alpha-particle. Now Wilson cloud-chamber observations showed that the β-particles from radio-iridium are negatively charged. Since the isotopes of iridium that would be expected to be radioactive with emission of electrons are 194, 195 and 196, which can go to stable platinum isotopes, it seems probable that the stable platinum isotopes Pt^{196} and Pt^{198} are involved in the iridium reaction. Thus for example

$$_{78}Pt^{196}+{}_{1}H^{2}\rightarrow{}_{97}Ir^{194}+{}_{2}He^{4}$$

$$_{97}Ir^{194}\rightarrow{}_{98}Pt^{194}+{}_{-1}e.$$

It is of course not possible to decide which of the two iridium activities is to be ascribed to the above reaction. This kind of a reaction of deuterons with Pt^{194} should yield Ir^{192}, which would presumably decay with the emission of a positron to form Os^{192}. These positrons have as yet not been observed.

The fact that the iridium activities were larger than the platinum activities leads to the definite conclusion that the maxima observed in the composite transmutation function are at least in large part (and probably entirely), due to the iridium activation. The interpretation of these maxima as an indication of resonance penetration of the deuteron as a whole into the platinum nucleus is consistent with the type of reaction here concerned. The platinum activity involving necessarily only the penetration of the neutron into the nucleus probably follows the Oppenheimer-Phillips transmutation function. Whether this is true cannot be decided from the present experiments, but remains for future investigation.

We acknowledge with thanks grants in support of this investigation from the Research Corporation, the Chemical Foundation and the Josiah Macy, Jr. Foundation. In addition, one of us (J. M. C.) is indebted to the Horace A. and Mary A. Rackham Trust Fund for valuable aid.

[8] These observed upper limits for the β-ray spectra are not precise. Probably the actual upper limits are somewhat higher, particularly in view of the theory of Uhlenbeck and Konopinski. (F. N. D. Kurie, J. R. Richardson and H. C. Paxton, Phys. Rev. **49**, 368 (1936).)