Radiochemical Study of Neutron-Deficient Chains in the Noble Metal Region*

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A radiochemical study of some neutron-deficient nuclides in the noble metal region has been undertaken, and several new chains identified. The method used to establish genetic relationships was that of timed chemical separations, where the parent activities are initially produced by cyclotron or linear accelerator bombardments. The following chains have been identified:

$$A=191:\ \mathrm{Hg}^{191} \xrightarrow{55\ \mathrm{min}} \mathrm{Au}^{191} \xrightarrow{3.0\ \mathrm{hr}} \mathrm{Pt}^{191} \xrightarrow{3.0\ \mathrm{day}} \mathrm{Ir}^{191},$$

$$A=189:\ \mathrm{Hg}^{189} \xrightarrow{\sim 20\ \mathrm{min}} \mathrm{Au}^{189} \xrightarrow{42\ \mathrm{min}} \mathrm{Pt}^{189} \xrightarrow{10.5\ \mathrm{hr}} \mathrm{Ir}^{189} \xrightarrow{11\ \mathrm{day}(?)} \mathrm{Os}^{189},$$

$$A=188:\ \mathrm{Pt}^{188} \xrightarrow{10.0\ \mathrm{day}} \mathrm{Ir}^{188} \xrightarrow{41\ \mathrm{hr}} \mathrm{Os}^{188},$$

$$A=187:\ \mathrm{Au}^{187} \xrightarrow{\sim 15\ \mathrm{min}} \mathrm{Pt}^{187} \xrightarrow{2.5\ \mathrm{hr}} \mathrm{Ir}^{187} \xrightarrow{14\ \mathrm{hr}} \mathrm{Os}^{187}.$$

INTRODUCTION

RECENT energy level studies[1–3] of odd-mass nuclei in the region $A=191$ through $A=197$ have shown that interesting regularities exist in the movement of proton and neutron energy levels as pairs of nucleons of the other kind are added. In this laboratory several isotopes of platinum and gold with mass number less than 191 had been observed in the course of other work, but a systematic radiochemical study of this region had not been pursued. Because of recent interest, however, it seemed worthwhile to search for and identify new neutron deficient chains in gold and platinum with $A\leq 191$ which might be susceptible to spectroscopic investigation. In this paper we report on the synthesis and identification of the following chains:

$$\mathrm{Hg}^{191} \rightarrow \mathrm{Au}^{191} \rightarrow \mathrm{Pt}^{191} \rightarrow \mathrm{Ir}^{191}$$

$$\mathrm{Hg}^{189} \rightarrow \mathrm{Au}^{189} \rightarrow \mathrm{Pt}^{189} \rightarrow \mathrm{Ir}^{189} \rightarrow \mathrm{Os}^{189}$$

$$\mathrm{Pt}^{188} \rightarrow \mathrm{Ir}^{188} \rightarrow \mathrm{Os}^{188}$$

$$\mathrm{Au}^{187} \rightarrow \mathrm{Pt}^{187} \rightarrow \mathrm{Ir}^{187} \rightarrow \mathrm{Os}^{187}.$$

EXPERIMENTAL METHOD

In the work reported here, targets of element Z were bombarded in general with protons from the 184-inch cyclotron to produce isotopes of element $(Z+1)$ by the (p,xn) reactions. The proton energy was varied between 50 and 130 Mev, to bring in various values of x. Some excitation function experiments were also performed with the 32-Mev proton beam of the Berkeley linear accelerator, and a few proton and heavy ion bombardments were made in the 60-inch cyclotron.

The Geiger counter decay curves of the primary $(Z+1)$ chemical fractions were in general so complex that their resolution was difficult at best and often unsuccessful. Consequently, half-lives and genetic chain relationships were often determined by means of the chemical "milking" technique introduced by Neumann and Perlman[4] and Karraker and Templeton.[5] In this method, chemical separations of daughter activities from the purified $(Z+1)$ fractions are made at a sequence of equal time intervals, the interval corresponding approximately to the expected half-life of the parent.

The number of atoms of a daughter substance present at a time t after purification of its parent is given by the formula

$$N_2=\frac{\lambda_1}{\lambda_2-\lambda_1}N_1^0(e^{-\lambda_1 t}-e^{-\lambda_2 t}).$$

The activity of the daughter is then

$$A_2=C_2\lambda_2 N_2=\frac{C_2\lambda_2\lambda_1}{\lambda_2-\lambda_1}N_1^0(e^{-\lambda_1 t}-e^{-\lambda_2 t}),$$

where C_2 is the counting efficiency of the daughter. Since the time interval between successive chemical separations is held constant, the exponential terms become a constant factor, and A_2 is proportional to the disintegration rate $(\lambda_1 N_1^0)$ of the parent at the beginning of each growth period. Thus, if one plots the logarithm of the initial activity of each daughter fraction against the time of separation, the slope of the line will correspond to the half-life of the parent.

Although the primary emphasis in this work has been on the radiochemical analysis, examination of the gamma-ray spectra of some of these neutron-deficient nuclides has also been made with a NaI(Tl) scintillation

* This work was performed under the auspices of the U. S. Atomic Energy Commission.
[1] de-Shalit, Huber, and Schneider, Helv. Phys. Acta **25**, 279 (1952).
[2] Gillon, Gopalakrishnan, de-Shalit, and Mihelich, Phys. Rev. **93**, 124 (1954).
[3] J. W. Mihelich and A. de-Shalit, Phys. Rev. **93**, 135 (1954).
[4] H. Neumann and I. Perlman, Phys. Rev. **78**, 191 (1950).
[5] D. G. Karraker and D. H. Templeton, Phys. Rev. **80**, 646 (1950).

spectrometer coupled to a 50-channel differential analyzer. These gamma-ray data are far from definitive, but they have been helpful in the identification of the various nuclides encountered, both new and old. Some of these data will be quoted here when they appear to provide relevant information.

RADIOCHEMICAL RESULTS

Figure 1 is a segment of an isotopic chart in the noble metal region showing the activities identified in the present study. The half-lives of previously reported activities are also given in parentheses.

The following is a summary of the experimental results given by mass number.

$A=191$. Genetics

Following a 120-Mev proton irradiation of gold metal, a pure mercury fraction was prepared by a procedure involving removal of the gold into amyl acetate and precipitation of mercury metal with $SnCl_2$. The decay curve of the mercury fraction itself was complex, with at least five components. Therefore, a series of seven timed gold separations was made from this fraction at intervals of eight minutes, by amyl acetate extraction. These gold "milkings" showed the

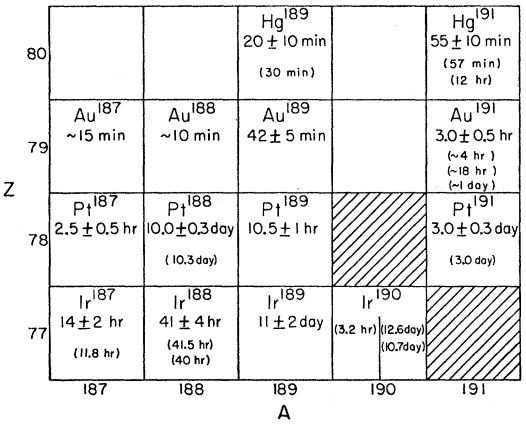

FIG. 1. Segment of an isotopic chart in the noble-element region (half-lives in parentheses are previously reported values).

activities and genetic relationships illustrated in Table I and Fig. 2.

The 40-minute gold activity is Au^{189}, and will be discussed under that mass number. The 3-hour and 3-day activities descend from the same mercury ancestor, whose half-life is ~50 minutes. Further chemical experiments with this gold "milking" fraction have identified the 3-hour activity as an isotope of gold and the 3-day activity as platinum, hence probably the daughter of the 3-hour gold. Since Pt^{191} is a fairly well known 3.0-day activity,[6,7] this chain can be assigned to

[6] G. Wilkinson, Phys. Rev. **75**, 1019 (1949).
[7] Swan, Portnoy, and Hill, Phys. Rev. **90**, 257 (1953).

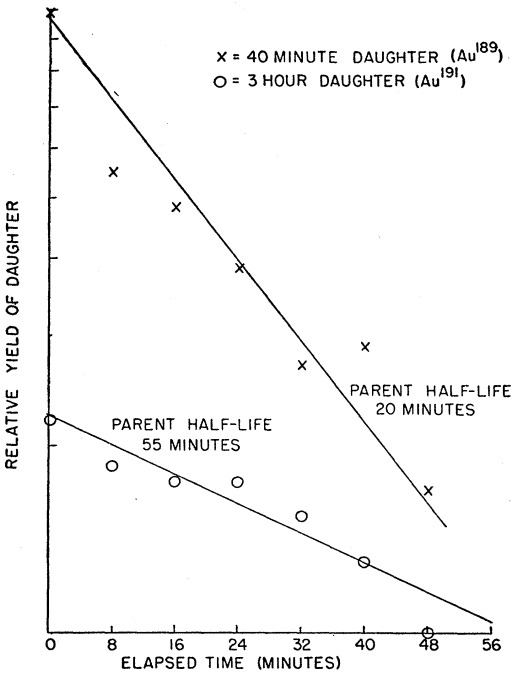

FIG. 2. Radiochemical yield of daughter activities as a function of time. Gold separated from parent mercury fraction at 8-minute intervals. (Bombardment: gold+120-Mev protons.)

mass 191.

$$Hg^{191} \xrightarrow{55\text{ min}} Au^{191} \xrightarrow{3\text{ hr}} Pt^{191} \xrightarrow{3.0\text{ days}} Ir^{191}.$$

These results are in agreement with the recent work of Gillon *et al.*,[2] who found in their study of conversion lines from 60-Mev proton bombardments of gold:

$$Hg^{191} \xrightarrow{57\text{ min}} Au^{191} \xrightarrow{\sim 4\text{ hr}} Pt^{191} \xrightarrow{3\text{ days}} Ir^{191}.$$

The genetic relationship between the 3-hour Au^{191} and 3.0-day Pt^{191} was also established independently in two other ways:

(a) Platinum was irradiated with 130-Mev protons, and a pure gold fraction prepared. Seven timed platinum separations were made at 30-minute intervals, with the results shown in Table II and Fig. 3.

This experiment indicates a half-life of 2.5±0.5 hours for Au^{191}. The other activities will be discussed under the appropriate mass numbers.

TABLE I. Genetic relationships. Gold separated from parent mercury fraction at 8-minute intervals. (Bombardment: gold +120-Mev protons.)

Activity	Half-life of Hg parent (or ancestor)	Assignment
40±10 min	20±10 min	Au^{189}
3.0±0.5 hr	55±10 min	Au^{191}
15 hr (weak)	>50 min	Au^{193}
3 day (weak)	~50 min	Pt^{191}

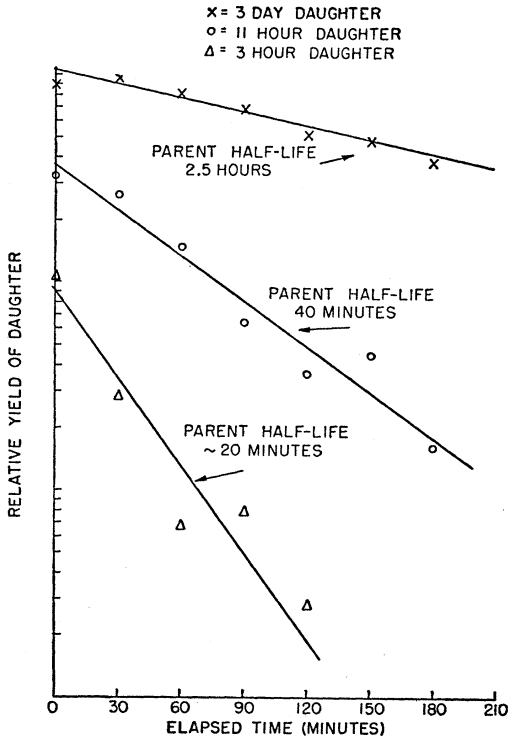

FIG. 3. Radiochemical yield of daughter activities as a function of time. Platinum separated from parent gold fraction at 30-minute intervals. (Bombardment: platinum+130-Mev protons.)

(b) Gold was irradiated with 120-Mev protons, and a pure mercury fraction separated. This was allowed to stand for about two hours, after which a gold separation was made from it. Five "milkings" of platinum were then made from this gold fraction at 3-hour intervals. The platinum milkings contained largely 3.0-day Pt^{191}, and the yields indicated a half-life of 3.0±0.5 hours for its gold parent.

Moon and Thompson[8] have reported an 18-hour Au^{191} descending from a 12-hour Hg^{191}. We have no evidence concerning the mercury isotope reported by these workers, but we can say that if such a Au^{191} isomer exists, it is not the parent of 3-day Pt^{191} within the limits of detection of the chemical genetic experiments reported here. A small amount of a 17-hour gold activity *was* observed in one of the gold fractions milked from mercury, but its gamma spectrum was shown to be identical (at 8 percent resolution in a scintillation spectrometer) to that of 17-hour Au^{193} and hence it is most likely Au^{193}.

TABLE II. Genetic relationships. Platinum separated from parent gold fraction at 30-minute intervals. (Bombardment: platinum+130-Mev protons.)

Pt activity	$T_{\frac{1}{2}}$ of gold parent	Assignment
3 day	2.5±0.5 hr	Pt^{191}
11±1 hr	40±10 min	Pt^{189}
3±0.5 hr	15–20 min	Pt^{187}

[8] J. H. Moon and A. L. Thompson (private communication, October 1952).

$A=191$. Gamma-Ray Spectra

The gamma spectrum of 3-hour Au^{191} was examined in the scintillation spectrometer with a sample which contained mostly that isotope; one of the spectra is shown in Fig. 4. Gamma rays were seen at 140±20 kev, 300±10 kev, 390±20 kev, 475±20 kev, and 600±20 kev, with intensities (corrected for counting efficiency) relative to the K x-rays of 0.1, 0.6, 0.05, 0.04, and 0.1, respectively. Because of the high intensity of the x-rays at ~60 kev, we cannot say anything about gamma radiation softer than ~100 kev.

In the course of several "milking" experiments, samples containing essentially pure 3-day Pt^{191} were obtained. Scintillation spectra taken with these samples

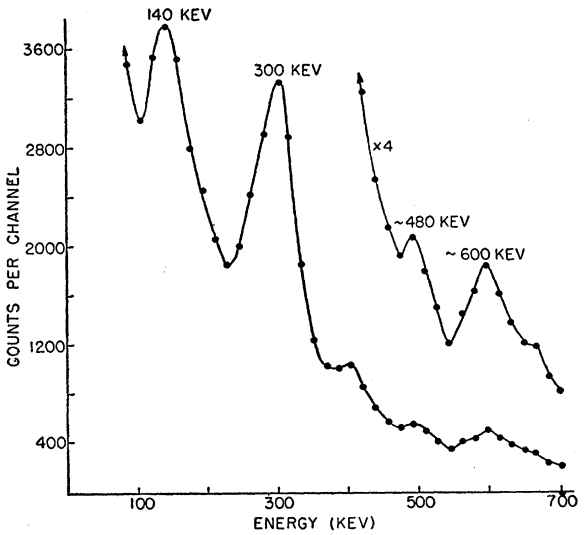

FIG. 4. Gamma-ray spectrum of Au^{191}.

showed, in addition to the K x-rays, gamma rays at 125±10 kev, 175±10 kev, 265±10 kev, 355±10 kev, 405±10 kev, 445±20 kev, and 530±10 kev. One of these scintillation spectra is reproduced in Fig. 5. The relative intensities of the 265, 355, 405, 445, and 530 kev gamma rays as determined from the areas under their photopeaks are 0.2, 1.00, 0.8, 0.2, and 1.7, respectively. The abundances of the 125- and 175-kev gamma-ray photopeaks were measured as 0.5 and 0.4 relative to that of the 345-kev gamma ray; however, the background under these peaks is rising sharply and there must also be some contribution from backscattered radiation, so these relative abundances are only estimates.

Swan, Portnoy, and Hill[7] have examined the conversion line spectrum of Pt^{191} and have reported gamma rays at 62, 82, 94, 125, 129, 171, 178, 267, 350, 359, 408, 455, and 537 kev. The present scintillation meas-

urements would of course not resolve the 125–129, 171–178, 350–359 pairs, but otherwise are in agreement with the results of Swan *et al.*, above 100 kev. (We could not examine the gamma-ray spectrum below 100 kev because of the overwhelming area of the K x-ray peak.)

$A=189$. Genetics

An ~12-hour activity in platinum was first observed in 1950 by Thompson and Rasmussen[9] from 50-Mev proton bombardments of iridium, but a mass assignment was not made at that time. With the aid of J. O. Rasmussen, this activity has now been assigned to Pt^{189} by means of proton excitation function experiments in which its yield from iridium is compared with that of 3.0-day Pt^{191} produced from the $(p,3n)$ reaction on Ir^{193}. The excitation experiments were done in the Berkeley 32-Mev proton linear accelerator with a set of stacked iridium and aluminum foils as targets and absorbers. Figure 6 shows the resulting yield curves,

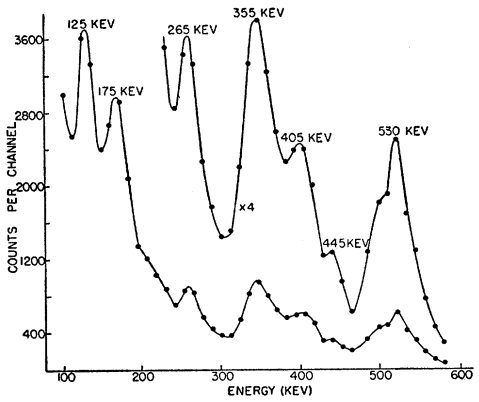

FIG. 5. Gamma-ray spectrum of Pt^{191}.

which exhibit similar maxima at ~28 Mev. On the basis of its production from a $(p,3n)$ reaction in iridium, the new activity can be only Pt^{189} or an isomer of Pt^{191}. The following is evidence against its assignment to Pt^{191m}: (a) we have bombarded iridium with 12-Mev protons in the 60-inch cyclotron, and observe in the platinum fraction the known 3-day Pt^{191} and 4-day Pt^{193m} which are produced from the (p,n) reaction. The 10-hour activity is not found. This is consistent with its assignment to Pt^{189}, because a $(p,3n)$ reaction is energetically not possible at this proton energy. (Anticipating the discussion of gamma-ray studies of the mass 189 chain, we also observed in this 12-Mev bombardment that the gamma spectrum of the platinum fraction was identical to the known spectrum of Pt^{191}, and had none of the gamma rays associated with the 10-hour platinum.) (b) Wilkinson, in his study of platinum isotopes produced by 18-Mev deuteron bombardments of iridium,[6] observed no platinum activity

[9] S. G. Thompson and J. O. Rasmussen (unpublished).

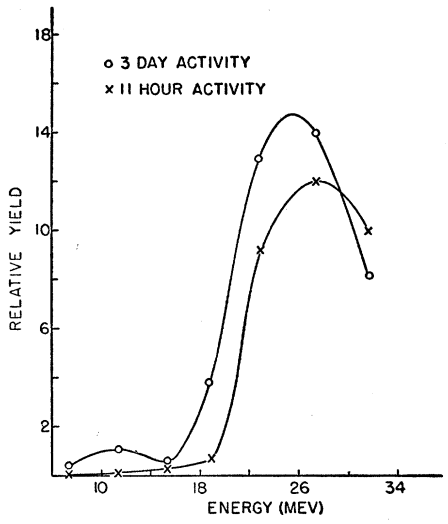

FIG. 6. Excitation curves for the production of 3-day Pt^{191} and 10-hour Pt^{189}.

with half-life shorter than that of 3-day Pt^{191}. He should not have been able to detect Pt^{189} because at 18 Mev the yield of the $(d,4n)$ reaction is quite small.

It is also noted from Fig. 6 that the yield curve for the 3-day component shows two maxima. The small peak at approximately 10 Mev indicates the production of 3-day Pt^{191} from the $Ir^{191}(p,n)$ reaction and of 4-day Pt^{193m} from the $Ir^{193}(p,n)$ reaction, while the tenfold larger peak at approximately 28 Mev corresponds to the $Ir^{193}(p,3n)Pt^{191}$ reaction. The 11-hour component shows no peak at approximately 10 Mev as might be expected if it were Pt^{191m}, but it seems to be produced only from the $(p,3n)$ reaction.

Because of these considerations we assign this activity to Pt^{189}. Our best value for its half-life is 10.5 ± 1 hours.

In the decay curves of the platinum fractions from these 32-Mev proton bombardments of iridium, an 11 ± 1-day activity also appears in addition to and in comparable yield to 10.5-hour Pt^{189} and 3.0-day Pt^{191}. A similar activity was seen in the decay curves of the iridium fractions (in addition to 75-day Ir^{192}). Attempts were made to establish the parentage of this 11-day activity by the timed separation procedure described above, but these were not successful because of lack of reproducibility of the iridium-platinum "milkings." Accordingly, platinum-iridium separations were performed on the initial platinum fractions after the "complete" decay of activities shorter than approximately 10 days, and it was found that an approximately 11-day activity appeared in both the platinum and the iridium fractions. The gamma-ray spectra of these activities were studied with the scintillation spectrometer, and were found to be different from each other (dispelling the fear of grossly incomplete chemical separation). The 11-day platinum activity is undoubtedly Pt^{188}; evidence for this will be discussed under $A=188$. That the 11-day iridium activity does

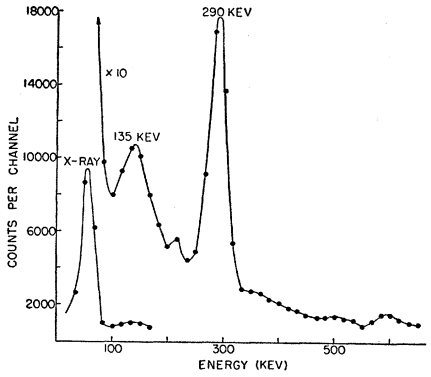

FIG. 7. Gamma-ray spectrum of Au^{189}.

not belong to the mass 188 chain was substantiated by showing that it is still produced at the lower proton energy of 25 Mev, whereas Pt^{188} is not seen. This energy should be below the threshold for the $(p,4n)$ reaction.

There remain three choices for the assignment of this activity: Ir^{191m}, Ir^{189}, or Ir^{190} arising from iridium impurity in the original platinum fractions. The first choice, Ir^{191m}, may probably be ruled out by the recent discovery of 6-second Ir^{191m} by Mihelich *et al.*[10] and by Naumann and Gerhart,[11] and also by the fact that we have searched for this activity following 12-Mev proton bombardments of iridium, with negative results.

Our data indicate that the 11-day iridium is Ir^{189}. However, Ir^{190} has also been reported[12,13] as an 11 to 13 day activity; in some of our milkings of iridium from platinum in which the 11-day iridium is observed, there is also seen a small amount of Ir^{192} which must have entered the original platinum fraction as an impurity. Because Ir^{190} would be present in the same way we cannot exclude the possibility that the 11-day iridium which we observe may be Ir^{190}. However, in the following discussion on the gamma spectra we shall refer to this isotope as Ir^{189}.

Once Pt^{189} has been identified it becomes easier to recognize its Au^{189} parent. This isotope has been produced in several different ways:

(a) Bombardments of tantalum ($Z=73$) with high-energy carbon ions in the 60-inch cyclotron produced activities in the gold fraction of half-lives 10 ± 5 minutes, 42 ± 5 minutes (predominant), $\sim$11 hour, and $\sim$10 day (weak). The yields were very low in these experiments because of inadequate beam currents, but timed platinum separations from the gold fraction indicated that the 11-hour platinum (189) is the daughter of an approximately 35-minute gold parent activity.

(b) Platinum metal was irradiated with 130-Mev protons, and a gold chemical fraction isolated. Timed milkings of platinum from this fraction (done in separate experiments at intervals of 10 minutes and 30 minutes, respectively) verified that 11-hour Pt^{189} has a gold parent of 40 ± 10-minute half-life. The yield curves from these milking experiments are shown in Figs. 3 and 14.

These experiments demonstrate that Au^{189} has a half-life of 42 ± 5 minutes.

In the experiment discussed under $A=191$ (the results of which are given in Table I and Fig. 2), it was seen that the 40-minute gold activity grew from an approximately 20-minute mercury parent. The experiments cited here which establish the 42-minute gold as Au^{189} therefore also set the half-life of Hg^{189} as approximately 20 minutes. This Hg^{189} half-life, however, is the result of only one experiment, so a considerable uncertainty is attached to this value.

The mass 189 chain, insofar as we have studied it, can be written as:

$$Hg^{189} \xrightarrow{\sim 20\text{ min}} Au^{189} \xrightarrow{42\text{ min}}$$

$$Pt^{189} \xrightarrow{10.5\text{ hr}} Ir^{189} \xrightarrow{10\text{ day}(?)} Os^{189}.$$

$A=189$. Gamma-Ray Spectra

A fairly pure Au^{189} sample was obtained from the carbon-ion bombardment of tantalum. Gamma-ray spectra taken during the first few hours of its decay show, in addition to x-rays, a very prominent gamma ray at 290 ± 10 kev, decaying with the approximately 40-minute half-life of Au^{189} (see Fig. 7). A gamma ray is also seen at 135 ± 10 kev in about 10 percent of the intensity of the 290-kev gamma ray. High-energy radiations (>800 kev) may also be present.

The Pt^{189} gamma-ray spectrum indicates a fairly certain photon at 140 ± 10 kev, with probable gamma radiation at $\sim$550 kev, slightly greater than 550 kev, and at $\sim$700 kev.

Bombardments of iridium with 32-Mev protons produce in the platinum fraction active isotopes of masses

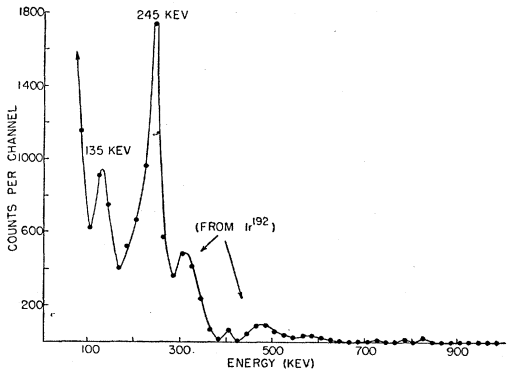

FIG. 8. Gamma-ray spectrum of Ir^{189}.

[10] Mihelich, McKeown, and Goldhaber, Phys. Rev. **96**, 1450 (1954).
[11] R. A. Naumann and J. B. Gerhart, Phys. Rev. **96**, 1452 (1954).
[12] L. J. Goodman and M. L. Pool, Phys. Rev. **71**, 288 (1947).
[13] T. C. Chu, Phys. Rev. **79**, 582 (1950).

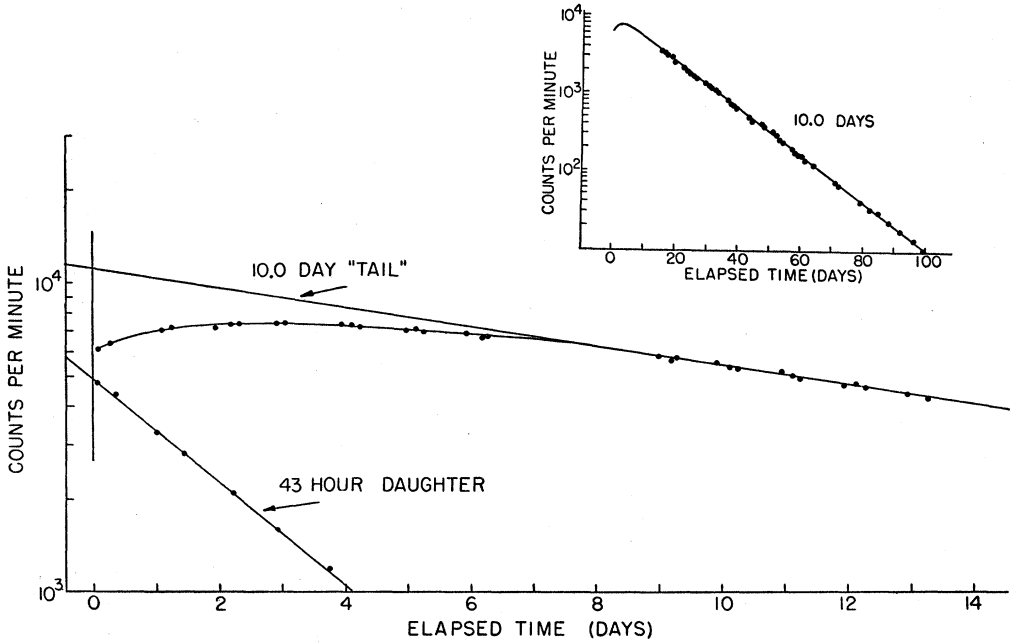

FIG. 9. Growth and decay curve for Pt^{188}, as daughter Ir^{188} grows into equilibrium with parent.

193, 191, 189, and 188. If one allows this fraction to decay for several weeks and then removes iridium from it, good samples of Ir^{189} and Ir^{188} are obtained, because Pt^{191} and Pt^{193m} have no active iridium daughters. The 11-day Ir^{189} can be distinguished from 41-hour Ir^{188} by virtue of their very different half-lives. We have obtained in this way the spectrum of Ir^{189} (see Fig. 8), which shows a strong gamma ray at 245 ± 10 kev, and perhaps a weak gamma ray at approximately 135 kev (although this may be backscattered 245-kev radiation). No other radiations than x-rays were seen which could be attributed to Ir^{189}.

$A=188$. Genetics and Gamma Spectra

Naumann[14] has reported the synthesis of a new neutron-deficient isotope of platinum, Pt^{188}, with a half-life of 10.3 days. Although the present work was aimed primarily toward the study of new odd-particle chains, it was of interest to examine the 188 chain because of the possibility of confusion of this 10-day Pt^{188} with the 10-day Ir^{189} reported here. (It has already been mentioned under $A=189$ that a 10-day activity had been observed in both the platinum and the iridium fractions from 30- to 50-Mev proton bombardments of iridium.)

We have studied the Pt^{188}-Ir^{188} pair in the following way: a proton bombardment of iridium metal was made at 32 Mev, and a platinum fraction chemically separated. This fraction was allowed to stand for about a month, at which time an iridium-platinum separation was performed. This second platinum fraction exhibited an initial growth, and then decayed with a 10.0 ± 0.3 day half-life. Analysis of the growth curve[15] plus direct decay data yields a daughter half-life of 41 ± 4 hours. This curve is shown in Fig. 9.

Our evidence for the assignment of the 10-day activity to Pt^{188}, in agreement with Naumann, is the following:

(a) We have observed this 10-day platinum in bombardments of iridium with 32-Mev protons, which is consistent with its production from the reaction $Ir^{191}(p,4n)Pt^{188}$.

(b) The daughter iridium activity has been assigned

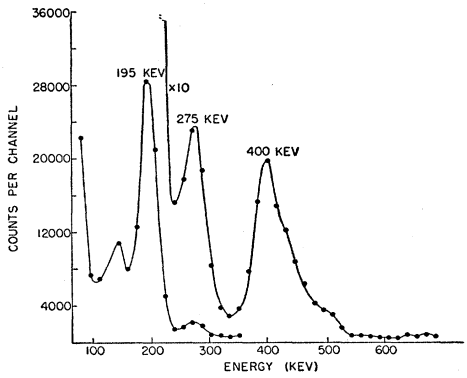

FIG. 10. Gamma-ray spectrum of Pt^{188}.

[14] R. A. Naumann, Phys. Rev. **96**, 90 (1954).

[15] The total amount of activity at time t can be expressed as $A=\sum_i a_i e^{-\lambda_i t}$, where the a_i's can be either positive or negative. To resolve this growth and decay curve, the "tail" was extrapolated back to the time of purification of the parent and subtracted from the observed curve. The series of negative differences, when plotted, gives the half-life of the daughter.

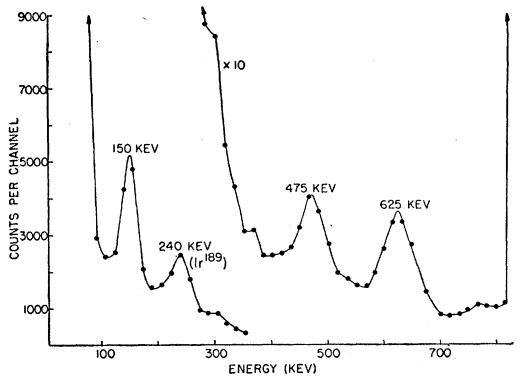

FIG. 11. Gamma-ray spectrum of Ir^{188}.

by Chu[13] to Ir^{188} on the basis of its production by an $(\alpha,3n)$ reaction on enriched Re^{187}.

(c) Our studies of the gamma spectrum of the 41-hour iridium (described below) show that the energies of the first two excited states in osmium which are populated by its decay are the same as those produced from the beta decay of Re^{188}. This is fairly convincing evidence for its assignment to Ir^{188}.

The gamma spectra of Pt^{188}, Ir^{188}, and of the Pt^{188}-Ir^{188} equilibrium mixture are shown in Figs. 10, 11, and 12, respectively. Gamma rays are seen in Pt^{188} at 195 ± 10 kev, 275 ± 15 kev, and there is a broad peak at approximately 400 kev which may represent two unresolved gamma rays. The measured relative abundances are 1.0, 0.1, and 0.3, respectively. As the Ir^{188} grows into the sample, gamma rays appear at 150 ± 10 kev, 475 ± 10 kev, and 625 ± 15 kev. The relative intensities were measured directly in the second iridium fraction which contains Ir^{188} plus a small fraction of Ir^{189} activity. From the pure Ir^{188} spectrum (Fig. 11) we obtain relative intensities 0.9, 0.6, and 1.0 for the three gamma rays, respectively. There also seems to be harder gamma radiation in low intensity.

Richmond, Grant, and Rose[16] have studied the beta decay of Re^{188} (which leads to the same daughter nucleus as does the electron capture decay of Ir^{188}) and have observed gamma rays of 152, 476, 638, 933, and ~1300 kev. The first three are in good agreement with the gamma rays observed by us from the decay of Ir^{188}; we have no comparison with the two high-energy gamma rays of Re^{188} other than to say that if the 933-kev gamma ray is present in the decay of Ir^{188} its intensity is less than one-third that of the 625-kev gamma ray.

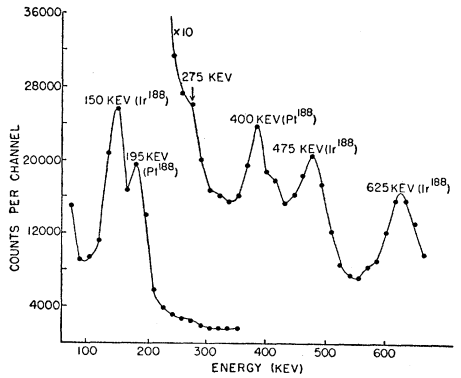

FIG. 12. Gamma-ray spectrum of Pt^{188} in equilibrium with Ir^{188}.

[16] Richmond, Grant, and Rose, Proc. Phys. Soc. (London) **A65**, 484 (1952).

In two 130-Mev proton bombardments where platinum was milked from a gold parent fraction, we have obtained preliminary evidence that the half-life of Au^{188} is of the order of 10 minutes. We have no further data concerning Au^{188}.

Our genetic data on the mass-188 chain are summarized as:

$$Au^{188} \xrightarrow{\sim 10 \text{ min}} Pt^{188} \xrightarrow{10.0 \text{ days}} Ir^{188} \xrightarrow{41 \text{ hr}} Os^{188}.$$

$A=187$. Genetics and Gamma Spectra

An 11.8-hour iridium isotope was discovered by Chu[13] and assigned by him to Ir^{187} on the basis of its production from an $(\alpha,2n)$ reaction upon Re^{185}. The shape of the excitation curve which he presents [as $(\alpha,2n)$ plus small contribution from $(\alpha,4n)$] is not convincing, however, especially in view of the fact that others have been unable to detect an $(\alpha,4n)$ reaction with 38-Mev alpha particles in the 60-inch cyclotron. Although our genetic data neither prove nor disprove this mass assignment, but only establish the gold and platinum activities which are isobaric with the 12-hour iridium, we shall here specify this reference activity as Ir^{187}. It will be seen, however, that our gamma-ray data tend to support this assignment.

TABLE III. Genetic relationships. Platinum separated from parent gold fractions at 7- and 10-minute intervals. (Bombardments: platinum+130-Mev protons.)

Activity	Half-life of gold parent or ancestor	Assignment
Experiment A—five milkings at 7-minute intervals		
2.5±0.5 hr	~13 minutes	Pt^{187}
12 ±2 hr	~14 minutes	Ir^{187}
Experiment B—eight milkings at 10-minute intervals		
3 ±0.5 hr	~17 minutes	Pt^{187}
12 ±2 hr	~12 minutes (plus ~40 minutes)	Ir^{187} (plus Pt^{189})

We have identified Pt^{187} in the following way: iridium metal was bombarded with 120-Mev protons and a pure platinum fraction chemically separated. (Its decay curve was complex, with components of $2\frac{1}{2}$ hours, ~10 hours, ~2.2 days, and ~10 days.) After allowing this platinum fraction to stand for one day, iridium was separated from it. This first iridium milking contained largely 14 ± 1 hour (Ir^{187}) and 43 ± 4 hour (Ir^{188}) activities, with a ratio (in counts per minute) of

Ir^{187}/Ir^{188} of 6.5. The same platinum fraction was then allowed to stand for an additional day, and iridium was again removed. The ratio (in counts per minute) of Ir^{187}/Ir^{188} present in this second milking was much lower, ~0.2. Because Ir^{188} grows from a "long"-lived parent (10-day Pt^{188}), its actual yield during the two intervals of growth is roughly constant and hence the ratio of Ir^{187}/Ir^{188} in the two milkings gives some idea of the half-life of the parent of Ir^{187}. By the factor of approximately 32 decrease in Ir^{187} in 24 hours, one would say that the half-life of its parent is approximately 5 hours. A possible error would arise from a small amount of 10-hour Pt^{189} impurity in the iridium milkings, which would cause the half-life of Pt^{187} to

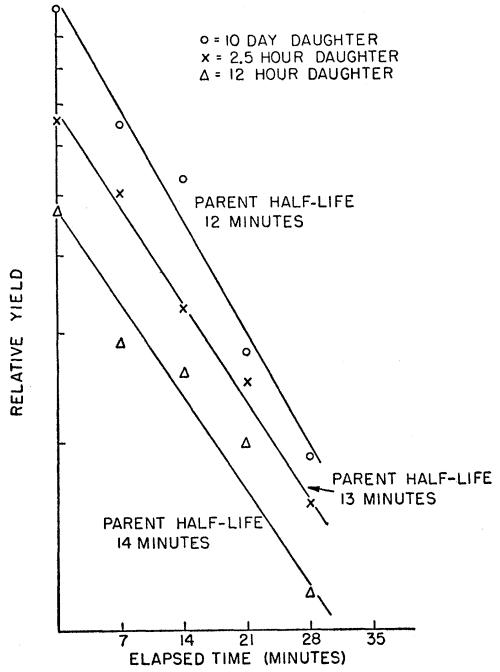

FIG. 13. Radiochemical yield of daughter activities as a function of time. Platinum separated from parent gold fraction at 7-minute intervals. (Bombardment: platinum+130-Mev protons.)

appear too long. The experiment, then, indicates that the half-life of Pt^{187} is ≤ 5 hours, and probably is the 2.5-hour platinum seen in the original platinum fraction.

Several other genetic experiments were done to identify the mass 187 chain. On two occasions, platinum metal was irradiated with 130-Mev protons, and pure gold fractions prepared. As was expected, the gold fraction decay curves were complex, with at least five components. Therefore, timed platinum milkings were made in each experiment by aqueous extraction of the platinum from the gold, which was in an amyl acetate solution. The results of these milkings are given in Table III, and some of the yield curves are shown in Figs. 13 and 14.

Our genetic data on the mass-187 chain are summarized as:

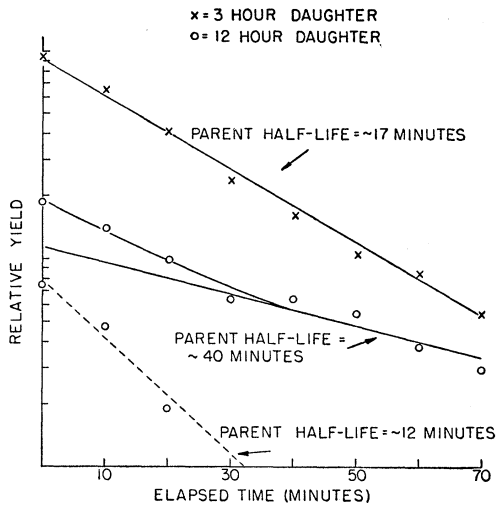

FIG. 14. Radiochemical yield of daughter activities as a function of time. Platinum separated from parent gold fraction at 10-minute intervals. (Bombardment: platinum+130-Mev protons.)

$$Au^{187} \xrightarrow{\sim 15\ \text{min}} Pt^{187} \xrightarrow{2.5\ \text{hr}} Ir^{187} \xrightarrow{14\ \text{hr}} Os^{187}.$$

The only reasonably good gamma-ray data at mass 187 were obtained with 14-hour Ir^{187}. Three gamma rays are seen, at 135±10 kev, 300±10 kev, and 435±15 kev, with relative intensities respectively 1.0/1.1/0.8. Weak gamma rays are also seen at ~500 kev and at ~625 kev, but these may belong in part to Ir^{188}. This spectrum is shown in Fig. 15.

One further remark may be made about the assignment of this chain to mass-187. In two bombardments of iridium with 32-Mev protons where fast chemistry was done, the 2.5-hour platinum activity has not been observed, whereas Pt^{188}, Pt^{189}, and heavier platinum isotopes are all found. We interpret this as evidence that this isotope has a mass lighter than 188, since it is produced from high-energy proton bombardments of iridium. Yet it could not be lighter than 186, or Chu[13]

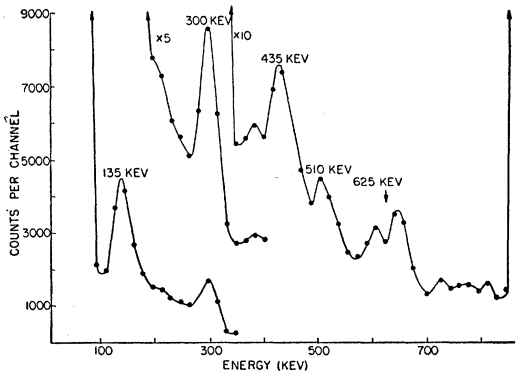

FIG. 15. Gamma-ray spectrum of Ir^{187}.

could not have produced it from an $(\alpha,3n)$ reaction on Re^{185}. Of the two remaining choices, mass 186 or 187, our gamma-ray data on the 14-hour iridium daughter lead us to prefer mass 187. The first two excited states of the even-even nucleus Os^{186}, defined by the beta decay of Re^{186}, are at 137 and 764 kev,[17,18] with gamma rays observed at 137, 627, and 764 kev. The principal gamma rays which we observe from the decay of the 14-hour iridium, however, are at 135, 300, and 435 kev. These do not fit into the Os^{186} level pattern, whereas in the case of mass 188, the gamma-ray energies which we observe from the decay of Ir^{188} agree quite well with those found[16] from the beta decay of Re^{188}.

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[17] F. R. Metzger and R. D. Hill, Phys. Rev. **82**, 646 (1951).
[18] L. Koerts, Phys. Rev. **95**, 1358 (1954).

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K-Shell Internal Conversion Coefficients*

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Internal conversion coefficients for the K-shells of several medium-energy gamma emitters have been measured with a solenoidal beta spectrometer and a 30 mg/cm² lead radiator. Isotopes investigated, with gamma energies and conversion coefficients $\times 10^3$, are as follows: Nb^{95}, 722 kev, 1.6±0.8; Cd^{110}, 657 kev, 2.2±0.8; Te^{122}, 570 kev, 6.6±1.7; La^{140}, 541 kev, 5.6±1.9; Ce^{140}, 489, 5.3±2.0. These values lead to multipolarity assignments of $E2$ or $M1$ for the first three, $E2$ for the La^{140}, and $E1$ or $E2$ for the Ce^{140}.

SEVERAL medium-energy gamma rays have been investigated and the K-shell internal conversion coefficients have been obtained. In addition, the ratios of some $K/(L+M)$ coefficients have been determined. The instrument used was a solenoidal type beta spectrometer previously described.[1] Sources were made in the form of a ring placed coaxially with the slits and set back from the point-source position by a distance equal to the radius of the ring. Gamma rays leaving the source at an angle of 45°±1° with the axis and converging on the point slit produced photoelectrons in the lead radiator at this position which were then accepted by the slit system at angles between 0 and 90° with the incident gamma ray. This geometry was employed in order to minimize the variation of the efficiency of the convertor with gamma energy.

TABLE I. Multipolarity of radiation from several nuclear transitions as determined from internal conversion ratios.

Isotope	γ-ray energy (kev)	$K/(L+M)$ This research	$K/(L+M)$ Previous research	$\alpha_K \times 10^3$ This research	$\alpha_K \times 10^3$ Previous research	Multipolarity
Nb 95	722	···	···	1.6±0.8	1.4[a]	$E2$ or $M1$
Cd 110	657	···	···	2.2±0.8	2.5[b]	$E2$ or $M1$
Te 122	570	2.3±0.4	[c]	6.6±1.7	4.9[d]	$E2$ or $M1$
La 140	541	5.2±0.5	6[e]	5.6±1.9	[c]	$E2$
Ce 140	489	4.2±1.4	3.7[e]	5.3±2.0	[c]	$E1$ or $E2$

[a] P. S. Mittleman, Phys. Rev. **99**, 94 (1954).
[b] K. Siegbahn, Phys. Rev. **77**, 233 (1950).
[c] No previous measurement.
[d] M. J. Glaubman and F. R. Metzger, Phys. Rev. **87**, 2039 (1952).
[e] R. E. Maerker and R. D. Birkhoff, Phys. Rev. **89**, 1159 (1953).

The coefficients were obtained from measurements of internal conversion spectra and photoelectron spectra using a 30 mg/cm² lead foil radiator. The efficiency of the convertors was found to be 0.03 percent from a comparison with the known values of the internal conversion coefficients of the 662-kev gamma from barium-137 and the 412-kev gamma from mercury 198. The data are summarized in Table I.

In several cases other measurements have been made but in most cases these have been obtained with different methods and geometries. In all cases the limits of experimental error overlap.

The 754-kev gamma ray reported by Mittelman[2] as due to zirconium-95 was observed in the photoelectron spectrum but was not observed in the internal conversion spectrum. The reason for this is believed to be partially the fact that the line is weak and only weakly converted and partially that it was not resolved from the 764-kev line of niobium-95.

A comparison has been made with theoretical calculations of the internal conversion coefficients[3] and a determination of the multipolarity of the radiation has been obtained. All results are summarized in Table I.

* This paper is based on a thesis submitted by R. C. Rohr in partial fulfillment of the requirements for the degree of Ph.D. in physics.
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[1] R. D. Birkhoff and F. Kalil, Phys. Rev. **91**, 505 (1953).
[2] P. S. Mittelman, Phys. Rev. **94**, 99 (1954).
[3] Rose, Goertzel, Spinrad, Haar, and Strong, Phys. Rev. **83**, 79 (1951).