Decay Scheme of Y^{92}†

WAYNE A. CASSATT, JR.,* AND W. WAYNE MEINKE
Department of Chemistry, University of Michigan, Ann Arbor, Michigan
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The gamma radiations of Y^{92} have been investigated with a scintillation spectrometer. The Y^{92} was produced in a cyclotron by a (d,α) reaction on zirconium and was not contaminated with Y^{91} or Y^{93} isotopes present in fission product solutions. Gamma rays of 0.21±0.01, 0.475±0.02, 0.94±0.03, 1.45±0.10, 1.9 ±0.10, and 2.4±0.10 Mev have been observed and both β-γ and γ-γ coincidences of the lower-energy lines tabulated. A decay scheme is proposed which is consistent with the experimental data and with recent data on Nb^{92} and Nb^{92m} reported in the literature.

I. INTRODUCTION

RECENT isotope tables and compilations of nuclear data[1,2] reveal that several of the isotopes of yttrium have been carefully characterized and their decay schemes determined. Half-life and beta-decay data for Y^{92} are also reported in these tables but no attempt has yet been made to formulate a decay scheme. This nuclide was previously observed by several workers as a fission product and also as a product of the (n,p) reaction on zirconium. Work in this laboratory[3] verified the mass assignment of this 3.6-hr activity to mass 92 by comparison of relative (d,α) reaction yields on the stable zirconium isotopes.

The half-life of Y^{92} was determined as 3.60±0.05 hours by Ames and his co-workers.[4] Values of 3.4, 3.5, and 3.6 Mev[1] have been reported for the maximum β-ray energy of this nuclide obtained by absorption methods. Ames *et al.*[4] studied this β-ray spectrum with a magnetic spectrometer and from their data postulated the presence of three β rays having maximum energies of 1.3, 2.7, and 3.60 Mev but do not give information regarding the relative intensities of these radiations. The γ-ray energies for this isotope were estimated by Hoagland and Katcoff[5] to be between 0.7 and 1.1 Mev by lead absorption. A search of the literature up to January, 1955 has revealed no additional work on this isotope. A chart showing the isotopes of niobium, zirconium, and yttrium given in Fig. 1 indicates the relationship of the various isotopes which might be found in low-energy deuteron bombardments of zirconium. Further information[1] on the radiations of the yttrium isotopes is given in Table I.

TABLE I. Nuclear characteristics for yttrium isotopes.

Isotope	Percent abundance	Type of decay[a]	Half-life	Energy of radiation in Mev: Particles	Energy of radiation in Mev: Gamma transitions
Y^{87m}		IT, no β^+	14 hr		0.384
Y^{87}		EC 99+% β^+~0.3%	80.0 hr	0.7	0.485, 0.390 (with Sr^{87m})
Y^{88}		EC 99+% β^+ 0.19%	104 day	0.83	0.908 (~99%) 1.853 (~99%) 2.76 (~1%)
Y^{89m}		IT	~14 sec		0.913
Y^{89}	100				
Y^{90}		β^-	61 hr	2.18	No γ
Y^{91m}		IT	51.0 min		0.551
Y^{91}		β^-	61 day	1.537	1.2, 0.2 (both 0.1%)
Y^{92}		β^-	3.60 hr	3.60, 2.7, 1.3	0.7–1.1
Y^{93}		β^-	10.0 hr	3.1	0.7
Y^{94}		β^-	16.5 min	5.4	1.4
Y^{95}		β^-	10.5 min		

[a] IT ≡ isomeric transition; EC ≡ electron capture.

II. EXPERIMENTAL METHODS[6,7]

The yttrium was produced by bombardment of high-purity zirconium metal foil with 7.8-Mev deuterons in the University of Michigan cyclotron. This foil (having natural isotopic abundances) was obtained from the Foote Mineral Company, Philadelphia, Pennsylvania and spectrographic analysis revealed the chemical impurities listed in Table II. The energy of the bombarding deuterons was such as to produce only isotopes of niobium, zirconium, and yttrium by (d,xn), (d,xnp), and (d,α) reactions on the zirconium. Smaller amounts of other products of these reactions could be expected from the chemical impurities. It has been found experimentally in this laboratory that the (d,α) reaction is energetically impossible for 7.8-Mev deuterons on an element of as high a Z as hafnium. For this reason no lutetium isotopes are present in the chemically separated samples in spite of the presence of several percent hafnium in the target material. For satisfactory characterization then, the yttrium products of the (d,α) reaction had to be chemically separated from a hundred- or thousand-fold excess of (d,n) and (d,p) reaction products of zirconium as well as from products of these reactions on the impurity elements.

* Present address: Phillips Petroleum Company, Bartlesville, Oklahoma.

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[1] Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953).

[2] *Nuclear Data*, National Bureau of Standards Circular No. 499 (U. S. Government Printing Office, Washington, D. C., 1950), including supplements and cards bringing table up to date.

[3] G. L. Schott and W. W. Meinke, Phys. Rev. **89**, 1156 (1953).

[4] Ames, Bunker, and Starner as given by reference 1.

[5] E. J. Hoagland and S. Katcoff, *Radiochemical Studies: The Fission Products* (McGraw-Hill Book Company, Inc., New York, 1950), Paper 73, p. 660, National Nuclear Energy Series, Plutonium Project Record, Vol. **9**, Div. IV.

[6] The equipment and techniques mentioned in this section are described in more detail in the doctoral thesis of W. A. Cassatt, Jr. (reference 7).

[7] Wayne A. Cassatt, Jr., Ph.D. Thesis, University of Michigan, September, 1954 (unpublished).

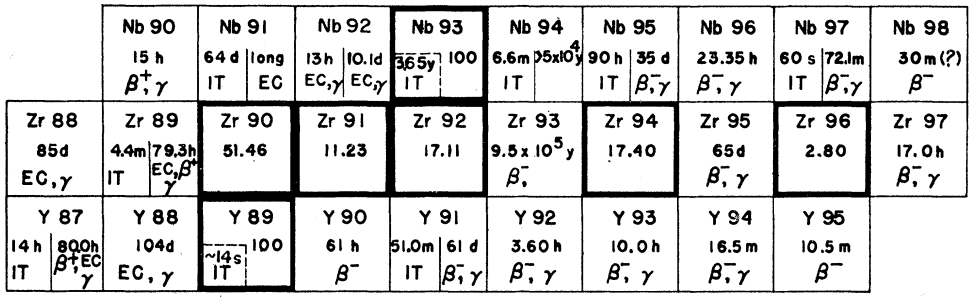

FIG. 1. Chart of niobium, zirconium, and yttrium isotopes.

The zirconium target was dissolved in hydrofluoric acid containing niobium and yttrium carriers, the precipitates digested, centrifuged, and washed. The yttrium fluoride precipitate was metathesized with concentrated potassium hydroxide solution, the hydroxide precipitate washed three times with water to remove the fluoride ion, and then redissolved in a minimum amount of HCl. More zirconium and niobium carriers were added, the zirconium and niobium precipitated by the addition of concentrated phosphoric acid and these phosphate precipitates centrifuged out, leaving the yttrium in the supernatant solution. This solution of yttrium was then recycled twice through the above procedure, the final hydroxide precipitate dissolved in a minimum amount of concentrated nitric acid, and an aliquot of the purified yttrium mounted for decay measurements.

The gross decay of the yttrium fraction was followed on both a scintillation well-type counter (Nuclear-Chicago Model DS-3) and a 4π proportional flow counter similar to that described by Borkowski.[8] These detectors were used in conjunction with a scale of 128 counting circuit. High-purity methane (99 mole percent minimum from Phillips Petroleum Company) was used as a counting gas.

A γ-ray scintillation spectrometer was used to study the γ-ray spectrum of a purified yttrium fluoride sample which was taken before the final hydroxide precipitation. This instrument utilizes as a detector a sealed 1-in. cube of NaI(Tl) coupled to a DuMont 6992 photomultiplier tube. The scintillation pulse is amplified by an Atomic Instrument Company Model 204B linear amplifier and fed into a Tektronix 514D oscilloscope, where the lines are recorded by a Polaroid Land camera. Pictures were taken of the spectrum appearing on the oscilloscope at various times after bombardment. An alternate system fed the pulses from the linear amplifier into an Atomic Instrument Company Model 510 single-channel pulse-height analyzer. The pulses selected by this analyzer trigger a counting rate meter whose output is plotted on a Leeds and Northrup Speedomax strip chart recorder.

For other data, the β-ray spectrum of an yttrium sample was measured with a survey β-ray spectrometer.[9] This instrument is a variable-field, 180° magnetic-type spectrometer with a four-centimeter focusing radius and utilizes a thin-window Geiger-Mueller tube as a detector. The yttrium sample was prepared by evaporating an aliquot of purified yttrium nitrate solution on a thin (0.00025-in.) Teflon film with the aid of an infrared heat lamp. The dry sample was then covered with another thin Teflon film which was held in place with rubber cement.

β-γ and γ-γ coincidence studies were also carried out on the 3.6-hr yttrium activity. The coincidence counter consists of two scintillation detectors feeding through linear amplifiers (Atomic Model 204B) into twin single-channel differential pulse-height analyzers (Atomic Model 510) which in turn trigger a coincidence analyzer (Atomic Model 502A). This setup makes possible the study of the coincidences occuring between various parts of the γ-ray spectrum of a sample, or between parts of the γ-ray spectrum in coincidence with portions of the β-ray spectrum when suitable scintillation crystals and/or absorbers are used.

In the β-γ coincidence measurements, a $\frac{3}{16}$-in. thick by $1\frac{1}{2}$-in. diameter *trans*-stilbene crystal was used in one scintillation detector to detect β rays and a 1 in. $\times 1\frac{1}{2}$ in. NaI(Tl) crystal was used in the other scintillation detector to count the γ rays. A beryllium absorber (2430 mg/cm^2), thick enough to stop the most energetic (3.6-Mev) β rays from the yttrium, was used between the sample and the NaI(Tl) crystal. No absorber was

TABLE II. Chemical impurities in zirconium target foil as determined by spectrographic analysis.

Element	Percent	Element	Percent
Al	0.04–0.08	Mo	0.001
Ca	0.003	N	0.004–0.04
Cr	0.001	Pb	0.001
Cu	0.007	Si	0.02
Fe	0.01–0.20	Sn	0.001
Hf	2.5–3.0	Ti	0.04
Mg	0.003	W	0.001
Mn	0.001		

[8] C. J. Borkowski and T. H. Handley, Oak Ridge National Laboratory Progress Report ORNL-1056, April, 1951 (unpublished), p. 1.

[9] Meinke, Cassatt, and Hall, "A Variable Field Survey Beta-Ray Spectrometer," AEC Nuclear Chemistry Project Report, University of Michigan, June 1954. Also Atomic Energy Commission Unclassified Document AECU-2944 (unpublished).

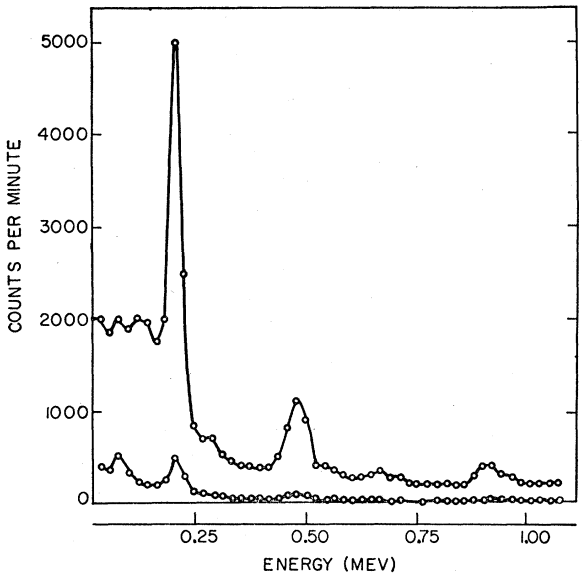

FIG. 2. Yttrium-92 γ-ray spectra. Top curve was taken three and one-half hours after the end of bombardment and ten and one-half hours before the lower curve.

used between the stilbene crystal and the sample. The base line and channel width of the single-channel pulse-height analyzer connected to the NaI(Tl) crystal were adjusted so that this analyzer passed on to the coincidence counter only those pulses lying within the energy region of one of the photoelectric peaks. The β-ray spectrum was then scanned in discrete steps with the single-channel pulse-height analyzer connected to the stilbene crystal. At each step the coincidence count rate and the gross count rate in each detector were recorded. This scanning was repeated for each of the four γ rays.

For γ-γ coincidence studies the stilbene crystal was replaced by a 1 in.$\times 1\frac{1}{2}$ in. NaI(Tl) crystal and a beryllium absorber (2640 mg/cm^2) was placed between this crystal and the yttrium sample. One of the single-channel pulse-height analyzers was set to count only those pulses under a given γ-ray photoelectric-peak. The γ-ray spectrum was then scanned with the other pulse-height analyzer. The gross counts and coincidence counts were recorded for each setting of the latter pulse-height analyzer. To reduce false coincidences arising from 180° Compton scattering from one crystal to another, a $\frac{1}{2}$-in. lead absorber was placed midway between the crystals with a $\frac{3}{8}$-in. hole in the center so that the sample could "see" both crystals.

III. RESULTS

Resolution of the decay curves taken with thin samples on the 4π proportional counter showed clearly that only three components, 3.6-hr, 61-hr, and 105-day, were present. Curves taken with the scintillation well counter showed a definite 3.6-hour component but were less conclusive for components of several days because of interference from the bremsstrahlung of the β-ray emitting 61-hour activity. Isotopes with these half-lives can be produced only by a (d,α) reaction upon the natural zirconium isotopes shown in Fig. 1. The short-lived Y^{89m} [which might be formed by a (d,α) reaction on Zr^{91}] and Y^{94} isotopes were not observed in this work since they had decayed out before the measurements were begun.

Analysis of the decay curves indicated that activities of intermediate half-lives were present in amounts less than a few percent as compared with the amount of the 3.6-hr activity. The absence of any 51-min, 10-hr, 14-hr, 80-hr or 61-day components in the decay curve indicates that the $(d,\alpha n)$ reaction does not occur to an appreciable extent at this deuteron energy. It also insures that the Y^{92} can be characterized without interference from radiations of these intermediate half-life isotopes, some of which would be present in good yields in fission product solutions and which could be discriminated against only by careful "milkings" of the strontium fission product parents. The absence of other components in the decay curve is further taken as proof that the yttrium was satisfactorily separated from the contaminating bombardment products of other elements in the target and also that no lutetium was formed as the result of a (d,α) reaction on the hafnium present in the target (the chemical procedure would not differentiate between yttrium and lutetium).

The γ-ray spectra[10] taken during the first few hours after bombardment show three strong peaks at 0.21, 0.475, and 0.94 Mev. Three weaker photolines were also observed at 1.45, 1.9, and 2.4 Mev. Spectra taken several days after bombardment show only a 0.90-Mev line and 1.8-Mev line, corresponding to lines reported for the 105-day Y^{88} isotope. These same two lines still persisted in the sample three months after bombard-

TABLE III. Energies, intensities and γ-γ coincidences of Y^{92} γ rays observed with scintillation spectrometers. (Errors are standard deviations.)

	Energy (Mev)	Rel. intensity (corrected)	γ rays in "coincidence" (Mev)
γ_1	0.21 ±0.01	1	0.48, 0.94
γ_2	0.475±0.02	1.1±0.1	0.21, 0.475, 0.94 (weak)
γ_3	0.94 ±0.03	1.9±0.4	···
γ_4	1.45 ±0.10	~1	0.21, 0.475, 0.94
γ_5	1.9 ±0.10	~0.1	···
γ_6	2.4 ±0.10	~0.02	···
		Other reported values	
From Nb^{92} [a]:			
γ_a	0.930	0.98	0.900, Zr x-rays
γ_b	0.900	0.01	0.930, Zr x-rays
γ_c	1.83	0.02	Zr x-rays
From Nb^{92m} [b]:			
γ_d	2.35		

[a] See reference 12.
[b] See reference 13.

[10] Pictures of these spectra and coincidence spectra referred to later in the paper can be found in reference 7.

ment and had decreased in intensity by a factor of approximately two.

Graphs of the lower-energy lines of the γ-ray spectrum of Y^{92} are shown in Fig. 2. A comparison of the original curves which are redrawn for Fig. 2 showed that the three γ-ray peaks at 0.21-, 0.475-, and 0.94-Mev decay with the same half-life. Oscilloscope pictures of these lines also show that the lower-intensity lines at 1.45(?), 1.9(?), and 2.4(?) Mev decay with roughly the same half-life as the three lower-energy lines. As further proof, intensity measurements on the 1.9-Mev line show it to be at least twenty times more intense than the 1.8-Mev line ascribed to the 105-day Y^{88} present in the sample. These six γ rays in the chemically purified sample were thus assigned to Y^{92} because they all appeared to decay with a half-life estimated to be between 3 and 4 hours.

The experimental energy and relative intensity values for the lines of Y^{92} are listed in Table III. Estimated errors are reported as standard deviations. The relative intensities of γ_1, γ_2, and γ_3 were obtained by integration of the area under the photoelectric peaks after subtraction of the background and the Compton distribution of the higher-energy γ rays. These areas were then corrected for the "photoelectric yield" of the crystal by use of the curves of McLaughlin and O'Kelley.[11] Relative intensities for γ_4, γ_5, and γ_6 were estimated from oscilloscope pictures and the same corrections applied.

The negative β-ray spectrum obtained approximately twelve hours after bombardment of the zirconium gave an end point of 3.6±0.2 Mev, while two days after bombardment it gave an endpoint of 2.2±0.1 Mev, characteristic of Y^{90}. The counting rate at 2.3 Mev of this two-component β-ray spectrum was followed down, giving a half-life of 3.4±0.1 hours. Next, the counting rate at the peak of the longer-lived β-ray spectrum remaining was followed down to background, giving a single half-life of 61±0.5 hours. These half-life and energy data were taken as adequate proof for assigning the 61-hour β ray to Y^{90} and the 3.4-hour β ray to Y^{92}.

A sweep of the positive β-ray spectrum showed no detectable amount of activity. This is to be expected since the only positron emitter produced in yttrium by a (d,α) reaction on zirconium would be the 105-day Y^{88} isotope which decays only 0.19% by β^+. The small number of disintegrations of this isotope would not have been detected by our equipment.

Curves were taken of β-γ and γ-γ coincidences covering the entire β-ray spectrum and including all γ rays except the weak ones at 1.9 and 2.4 Mev. All the observed coincidence data were corrected by standard methods for random or chance coincidences and background coincidences due to cosmic-ray showers. These curves show the 0.475-, 0.94-, and 1.45-Mev γ rays to be in coincidence with β rays beyond 1.3 Mev, while the 1.45-Mev γ ray is in coincidence only with β rays up to 1.3 Mev. Data on the 0.21-Mev γ ray were inconclusive.

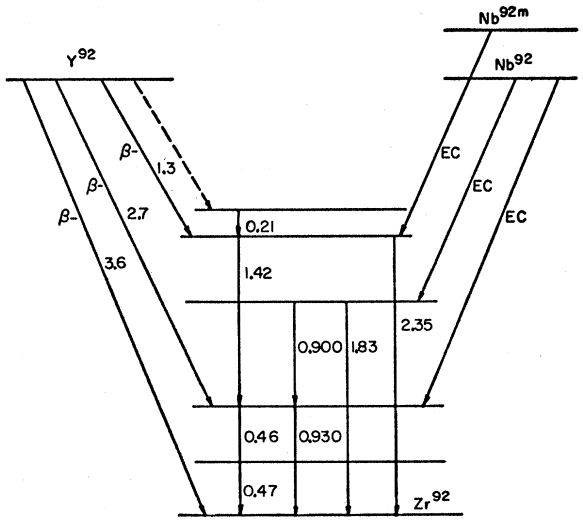

FIG. 3. Proposed decay scheme for yttrium-92.

The results of the γ-γ coincidence experiments are shown in Table III. No curves were taken for the 0.94-, 1.9-, and 2.4-Mev γ rays.

IV. DISCUSSION

The γ-ray energy and coincidence data obtained in this work should correlate with levels of Zr^{92} reported in the work of other laboratories. Hayward, Hoppes, and Ernst[12] have recently reported the energies and abundances of three γ rays of Nb^{92} as shown in Table III. In addition, James[13] has reported a 2.35-Mev γ ray associated with what he considers to be an isomer of Nb^{92m}.

The decay scheme shown in Fig. 3 is consistent with most of these experimental data. The β-ray energies are those listed by Ames *et al.*[4] since their instrument apparently gave better resolution of the individual β rays than did the instrument used in this work. The 1.1-Mev β-ray transition suggested in this decay scheme was not observed. The large relative intensity of the 0.94-Mev photopeak, however, precludes the possibility of placing the 0.21-Mev γ ray in cascade with the 3.6-Mev β ray. It would undoubtedly have been difficult for Ames *et al.* to completely resolve two such low-energy β rays (1.0 and 1.3 Mev) in this complex spectrum.

The width of the γ_2 and γ_3 lines in the γ-ray spectrometer curves would seem to indicate that they might actually consist of two γ rays each. From γ_2, there can be readily resolved two γ rays of 0.46±0.02 and 0.49±0.02 Mev energy. Similarly, from γ_3 there can be

[11] P. W. McLaughlin and G. D. O'Kelley, California Research and Development Company Report MTA-40, September, 1953 (unpublished), p. 11.

[12] Hayward, Hoppes, and Ernst, Phys. Rev. **98**, 231 (A) (1955).

[13] R. A. James, Phys. Rev. **93**, 288 (1954).

resolved with difficulty two γ rays of 0.92 ± 0.03 and 0.96 ± 0.03 Mev.

The γ_2 doublet appears to correlate best with the more precise energy values of Hayward *et al.*[12] if placed in cascade with the 1.45-Mev γ ray. Their 1.83-Mev γ ray corresponds well with the 1.9-Mev γ ray reported here and the 0.94-Mev line appears to be indeed a doublet. Their intensity ratio for the 1.83-Mev line relative to the 0.930-Mev line agrees quite well with that obtained from Y^{92}.

James[13] recently reported a new 13-hour activity in niobium which he assigned to an isomer of Nb^{92}. This assignment was based primarily on the similarity between the (p,pn) excitation function of this activity and that of the 10-day Nb^{92}. He states that the isomer emits K x-rays of zirconium and a γ ray whose energy was determined to be 2.35 Mev by a scintillation spectrometer. This γ-ray energy fits well into the level scheme proposed in Fig. 3 and would seem to substantiate the assignment of the 13-hour activity to Nb^{92m}. While one might expect that the 1.42- and 0.47-Mev γ rays would have been also reported as present, they may have been obscured by the 0.93- and 1.83-Mev γ rays of the more abundant 10-day Nb^{92}.

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Metastable States of Re^{180}, Ir^{191}, Au^{193}, Pb^{201}, and Pb^{203}†*

VERA KISTIAKOWSKY FISCHER
Radiation Laboratory, University of California, Berkeley, California, and Columbia University, New York, New York

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Ten elements of atomic number between 60 and 82 have been bombarded with 31.5-Mev protons and examined for activities with half-lives between 0.5 and 200 seconds. None were observed in Sm, Ho, Tm, Lu, and Ta. Those produced in W, Ir, Pt, Au, and Tl were investigated with scintillation and proportional counters. Isotope assignments were made on the basis of excitation function studies. Observed were Re^{180m} (145 seconds), Ir^{141m} (4.9 seconds), Au^{193m} (3.9 seconds), Au^{195m} (31 seconds), Au^{197m} (7.4 seconds), Pb^{201m} (60 seconds), and Pb^{203m} (6.7 seconds). Decay schemes are proposed and some regularities are discussed.

INTRODUCTION

IN agreement with considerations based on the shell model it has been observed that many isotopes in the region between atomic number 60 and 82 have low-lying metastable states. It has further been pointed out[1,2] that there is a grouping within this region defined by closed nucleon shells: the density of cases of nuclear isomerism increases sharply at the upper end of the region, there being seven observed cases with $Z=60$ to 72 and twenty-four, with $Z=72$ to 82. In order to determine whether this effect is due solely to insufficient study of the lower end of the region, a search for new cases of isomerism was undertaken.

Ten elements have been bombarded with 31.5-Mev protons and examined for activities with half-life between 0.5 and 200 seconds. These experimentally set limits include the expected half-lives of $M3$ and $E3$ transitions of energy <200 kev, $M4$ and $E4$ transitions of energy >500 kev and energetic beta-decay transitions. Since a number of nuclear reactions are possible at the maximum bombarding energy, excitation function studies were performed to permit isotopic assignment of the observed activities.

EXPERIMENTAL

I. Bombardment and Counting Arrangement

The ten targets which were bombarded are $_{62}$Sm (>98%),[3] $_{67}$Ho (>99%),[3] $_{69}$Tm (>96%),[3] $_{71}$Lu (>98%),[3] $_{73}$Ta (>99%), $_{74}$W (>99%), $_{77}$Ir (99.5%), $_{78}$Pt (>99%), $_{79}$Au (>99%), and $_{81}$Tl (99.8%). All of these were in the form of the metal and the numbers in the brackets indicate their elemental purity excluding oxygen contaminations from the formation of oxide coatings.

The bombardments were performed at the University of California Radiation Laboratory linear accelerator. The beam was focused into a spot $\frac{3}{16}$ inch by $\frac{5}{8}$ inch by a strong-focusing magnet consisting of four quadrupole lenses. In addition, to make certain that the beam did not strike the target holder, a collimator was placed immediately before the target position. The energy of the protons from the linear accelerator is 31.5 ± 0.5 Mev; for excitation function studies the desired energies

† This work was sponsored in part by the U. S. Atomic Energy Commission.
* This work was made possible by the Sarah Berliner Fellowship (1953–54) of the American Association of University Women.
[1] M. Goldhaber and R. D. Hill, Revs. Modern Phys. **24**, 179 (1952).
[2] J. W. Mihelich and A. de-Shalit, Phys. Rev. **93**, 135 (1954).
[3] On loan from Dr. F. H. Spedding, Ames Laboratory, Ames, Iowa.