decay of Tb^{157} can be calculated if the L to K-capture ratio is known.[16] This ratio is found to be 2.64 for Tb^{157} from the unscrambling data. The transition energy calculated by using the approximate formula is 60 keV. This value is of the same order of magnitude as the 20 keV estimated from experimental data together with the orbital assignments made based on the collective model of the nucleus.[8]

[16] H. Brysk and M. E. Rose, Revs. Modern Phys. **30**, 1169 (1958). R. Bouchez and P. Depommier, *Reports On Progress in Physics* (The Physical Society, London, 1960), Vol. 23, p. 395, Formula 71.

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Characterization of Ru^{107}, Ru^{108}, Rh^{107}, and Rh^{108}†

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The mass number of Rh^{107} (21.7±0.4 min) has been confirmed by alpha bombardments of Ru^{104} at selected energies, by fast-neutron bombardment of Pd^{108}, and by chemical identification; and the mass number of Rh^{108} (16.8±0.5 sec) has been established by the nature of its γ radiations. The mass numbers of the two precursors Ru^{107} (4.2±0.3 min) and Ru^{108} (4.5±0.2 min) have thereby also been established. The main radiations associated with these species are as follows (energies in keV): Ru^{107} β groups of 2100±300 and 3150±300, γ rays of 195 (14%, coincident with the 2100 β), 370 (~6%, coincident with the 195 γ), 480 (weak, seen only in coincidence with the 195 γ), 860 (7%, coincident with the 195 γ), 930 (4%), 1030 (4%), and 1290 (4%); Ru^{108} β groups 1150±100 and 1320±100, a γ of 165±3 (28%, coincident with the 1150 β); Rh^{107} β groups 840±40, 940±70, 1140±50, and 1200±50 keV, γ rays of 115 (0.5%), 285 (~3%, seen only in coincidence with the 390 γ), 307 (73%, coincident with the 1200 β), 365 (~2%, coincident with the 307 γ), 390 (11%, coincident with the 1140 and 840 β groups), 470 (1%), 570 (2%, coincident with the 940 β), and 675 (3%, coincident with the 840 β), and γ coincidence-sum lines at 680 (~3%), 880 (very weak), and 1140 (≤0.5%); Rh^{108} β of 4500±600 keV, γ rays of 430 (43%), 510 (10%, partly coincident with the 430 γ), 620 (22%, coincident with the 430 γ), 1520 (5%), and 2000 (≤3%). No 940 γ from the Pd^{108} 940 level could be detected (<3%), and less than one-third of the 510 γ rays follow β transitions to the 940 level. All γ rays above 115 in the four species are in fast coincidence with β rays. There are other γ rays associated with these species, especially for Ru^{107} and/or Rh^{108} above 1500. No evidence was found for isomers of Pd^{107}, Rh^{107}, Pd^{108}, or Rh^{108} from decay of 21.7-min Rh^{107} or 16.8-sec Rh^{108}. No Rh^{107} or Rh^{108} isomers could be isolated. However a γ ray of 21 keV, presumed to be K x rays of rhodium, appears in the short-lived ruthenium spectrum, with an intensity 5 to 8% relative to Ru^{107}; this is attributed to a short-lived (<10 sec) Rh^{107} isomer formed in >8% of the Ru^{107} disintegrations. The following decay paths are proposed: decay of Ru^{107} (Q^β=3200) proceeding to Rh^{107} excited levels of 1290 (4%), 1030 (11%), 930 (4%), 675 or 1530 (<5%), 565 (~6%), and 195 (0 to 5%), and to ground state (74%), with the reservation that it is likely that some of these levels should be referred to the supposed isomeric level rather than to the ground level; decay of Rh^{107} (Q^β=1510) proceeding to Pd^{107} levels of 1140 (~0.2%), 675 (may be more than one level, 7%), 570 (2%), 470 (1%), 390 (8%), and 307 (71%), and to ground state (0 to 17%); decay of Ru^{108} (presumably 0+, Q^β=1320) proceeding to Rh^{108} levels of 165 (0+ or 1+, 28%) and ground state (1+, 72%); decay of Rh^{108} (1+, Q^β=4500) proceeding to Pd^{108} levels of 2000 or higher (≤3%), 1520 or higher (≥5%), 1050 (0+, 22%), 940 (2+, 0 to 5%), and 430 (2+, ~17%), and to ground state (0+, 51%). Interpretations of these schemes are presented.

INTRODUCTION

THE fission of uranium is expected[1,2] to produce ruthenium isotopes from Ru^{101} to beyond Ru^{110}. Beside stable Ru^{101}, Ru^{102}, and Ru^{104}, the β emitters 40-day Ru^{103}, 4.5-h $Ru^{105} \rightarrow$ 45-sec Rh^{105m}+36-h Rh^{105}, and 1.0-yr $Ru^{106} \rightarrow$ 30-sec Rh^{106} are known.[1,3,4] Glendenin showed[5] in 1944 in a study of the chain 4-min Ru → 22-min Rh, discovered by Born and Seelmann-Eggebert,[6] that the yield of 22-min Rh was only about half of that expected from the 4-min Ru, and he proposed that the 4-min activity was a mixture of Ru^{107} and Ru^{108} of almost the same half-period, the latter producing a short-lived Rh^{108} decaying to stable Pd^{108}.

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[1] *Radiochemical Studies: The Fission Products*, edited by C. D. Coryell and N. Sugarman, National Nuclear Energy Series, Plutonium Project Record (McGraw-Hill Book Company, New York, 1951), Div. IV, Vol. 9.

[2] C. D. Coryell, M. Kaplan, and R. D. Fink, Can. J. Chem. **39**, 646 (1961).

[3] D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 585 (1958).

[4] *Nuclear Data Sheets*, edited by C. L. McGinnis, (National Academy of Sciences—National Research Council, Washington, D. C., 1958).

[5] L. E. Glendenin, reference 1, Paper 115.

[6] J. H. Born and W. Seelmann-Eggebert, Naturwissenschaften **31**, 420 (1943).

The Rh^{108} was later isolated[7,8] and found to have the half-period 18 sec. It has been generally assumed, according to evidence summarized below, that 107 and 108 are the mass assignments.

First, rough measurements of beta decay energies (Ru^{107} about 4 MeV,[6,7] Rh^{107} about 1.25 MeV,[6,7] Rh^{108} about 4 MeV[7,8]) are in the neighborhood of what one would expect from beta systematics[9] for mass numbers 107 and 108. Second, these species have been shown[5,7] not to decay into radioactive palladium isotopes, and this finding rules out mass numbers 109, 111, or higher. Finally, bombardment of palladium of natural isotopic composition with fast (up to about 31 MeV) neutrons is reported[7,8] to have produced the 4-min Ru → 22-min Rh, presumably by the reaction $Pd^{110}(n,\alpha)Ru^{107}$. As the species which could have been formed by (n,α) reactions on the other stable palladium isotopes are all well characterized, this was taken to be sufficient evidence that the mass number of the 4-min Ru → 22-min Rh chain is 107. However, at such bombarding energies there are many reactions which can produce ruthenium from palladium. Thus, though it seems likely that the mass assignments given these chains are correct, the evidence is not conclusive. One of the objectives of the present study,[10] then, is to establish the mass numbers of these two chains.

Another objective of this study is to determine, as far as possible, the energies and the yields of the radiations associated with these species. From such information, deductions may be made about the nuclear levels involved. It is of interest to compare the results of such deductions with the predictions of nuclear models and with trends indicated by neighboring nuclides.

We have already listed the beta radiations that are reported in the literature for these species. The gamma radiations that have been reported are as follows (energies in keV): Ru^{107} 220;[8] Rh^{107} 315;[7] 95, 145, 305, 390 and 475;[11] 305, 385 (coincident with 305), 570, and 680;[12] 305 and 570;[8] Rh^{108} 430.[8] The results which will be presented in this paper will be seen to be in disagreement with some of these data.

No evidence has been found for ruthenium isotopes of mass number 109 or higher, suggesting that these have half-periods of less than 30 sec. The 4.5-h Ru^{105} is the only other fission-product ruthenium of half-period short enough to interfere significantly in this study of the two 4- to 5-min ruthenium isotopes. Fortunately the decay properties of it and of its Rh^{105} descendants (45-sec and 36-h isomers) are well known,[13–18] so that suitable corrections can be made. In this study, all the γ rays associated with fission-product short-lived ruthenium isotopes and their decay products were found to have half-periods attributable to the mass chains 105, 107, and 108.

EXPERIMENTAL

The fission products were usually made by short bombardments (0.25 to 2 min) of uranium foils with 15-MeV deuterons at the MIT cyclotron. Sources of rhodium and palladium for study were prepared by first separating ruthenium from the fission products and then milking the rhodium or palladium from the ruthenium progenitor, except that β-γ and γ-γ coincidence measurements on 16.8-sec Rh^{108} were carried out using a ruthenium source with the species in equilibrium with its Ru^{108} parent. The chemical procedures normally employed were modifications of older procedures, involving $HClO_4$ distillation[19] of ruthenium as RuO_4 followed by either reduction and precipitation[19] of ruthenium as RuO_2, or precipitation[20] of rhodium as $K_3Rh(NO_2)_6$, or extraction[21] of palladium as the dimethylglyoxime complex from HCl solution into chloroform. For some of the experiments, weightless sources of 21.7-min Rh^{107} were prepared by a procedure derived from a method recently developed[22] for the preparation of carrier-free rhodium, involving adsorption of the rhodium on filter paper and subsequent elution, after separation of the Ru^{107} parent as RuO_4 by $HClO_4$ distillation. Counting of ruthenium usually began 5 to 8 min after bombardment. Separation of rhodium daughters from ruthenium, when done, was carried out at a time after ruthenium separation which was appropriate to the species being studied. In order to make certain that other fission products were not contaminating the ruthenium and rhodium sources, most of the experiments were repeated with variations in the chemical procedures, such as redistillation or reprecipitation.

The β spectra of the ruthenium and rhodium sources were obtained with Pilot B plastic scintillators (Pilot Chemicals, Inc., Watertown, Massachusetts) of various

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[17] Atam P. Arya, Bull. Am. Phys. Soc. **6**, 428 (1961).

[18] W. R. Pierson and H. C. Griffin (unpublished).

[19] L. E. Glendenin, reference 1, Paper 260.

[20] J. A. Seiler, reference 1, Paper 262.

[21] J. A. Seiler, reference 1, Paper 264.

[22] M. H. Kurbatov and C. W. Townley, J. Inorg. Nuclear Chem. **18**, 19 (1961).

sizes ranging from 0.20 cm thick×1.20-cm diam to 3.20 cm thick×5.08-cm diam. The γ-ray spectra were obtained with NaI(Tl) crystals ranging from 1.27 cm thick×3.81-cm diam to 7.6 cm×7.6 cm, with 1850 mg/cm^2 (1.0 cm) of beryllium (for Rh^{107} sources) or 2570 mg/cm^2 (for Rh^{108} or short-lived ruthenium sources) as a β absorber. The detectors were enclosed in a large copper-lined lead shield and mounted on DuMont phototubes of appropriate sizes, the output pulses of which were sent to a 256-channel pulse sorter.

The β-γ coincidence measurements were made with appropriate plastic scintillators and NaI(Tl) crystals and a fast-slow coincidence circuit ($2\tau=1.5\times10^{-7}$ sec), gating on a region of the β spectrum and displaying the coincident γ spectrum on the multichannel pulse sorter or, conversely, gating on a portion of the γ spectrum and displaying the coincident β spectrum. In the case of 21.7-min Rh^{107} weightless sources were used.

The γ-γ coincidence measurements were made with two NaI(Tl) crystals of appropriate sizes, in the manner just described for the β-γ coincidence measurements ($2\tau\approx6\times10^{-8}$ sec). The γ-γ coincidence measurements were also made with two 7.6×7.6-cm NaI(Tl) crystals and a coincidence sorter[23] of a type called the XYZ Analyzer, which makes a photographic presentation of all coincidences simultaneously. Coincidence intensities may be estimated only qualitatively with this instrument, but energies may be read with fair accuracy. Other work was done by means of coincidence summing, that is to say by comparing low-geometry (about 3%) and high-geometry (about 40%) spectra, using a 7.6×7.6-cm NaI(Tl) crystal. Experiments were performed to determine the members of the cascade from the 680-keV level of Pd^{107}, using two NaI(Tl) crystals and a summing circuit to select coincident events whose sum corresponds to 680±20 keV.

One problem of this investigation is that of distinguishing the γ rays associated with Ru^{107} from those associated with Ru^{108}. One way of doing this is to obtain γ spectra coincident with appropriate portions of the $Ru^{107,108}$ β spectrum or vice versa, using the β-γ coincidence arrangement described earlier, and this was done. The validity of this procedure lies in the great difference in decay energy between Ru^{107} and Ru^{108}. The decay energies of Ru^{107} and Ru^{108} were also obtained in this way.

Another way of dealing with this problem is to produce Ru^{107} free of Ru^{108} or vice versa. To this end, and also to support the mass assignment 107 for the chain 4-min Ru → 22-min Rh, several attempts were made to produce Ru^{107} by the reaction $Pd^{110}(n,\alpha)Ru^{107}$ using palladium of natural isotopic composition and fast neutrons produced by bombardment of beryllium and lithium each with 15- and 20-MeV deuterons and separating ruthenium by $HClO_4$ distillation. The resulting activity contained 4.5-h Ru^{105} but no Ru^{107} was observed.

However, the same purpose can be accomplished by varying the relative fission yields of Ru^{107} and Ru^{103}. Therefore, bombardments of uranium and U^{235} with fast neutrons, uranium and thorium with 30-MeV alphas, uranium with pile neutrons, and thorium with 15-MeV deuterons were carried out. Ruthenium was separated in the usual way,[19] and the γ spectra of the ruthenium produced by the various methods were intercompared.

In order to convert the γ-intensity data into probability values (the procedure for doing this will be described later), it was necessary to know the percentage of 21.7-min Rh^{107} disintegrations giving rise to the 307-keV γ. This was determined by several methods, including:

(1) estimating the β branching ratios by analysis of the β spectrum,

(2) β-γ coincidence counting; in order to use this method, the efficiency of the γ detector must be known, and this was determined by means of the 320-keV γ from a Cr^{51} source calibrated to ±1%,

(3) estimation from gross counting of β and γ radiations from a single source, using calibrated β counters of both the scintillation and proportional types, and a calibrated γ scintillation counter; the β counters were calibrated with Sr^{89} or Au^{198}, and the γ counters with Cr^{51} or Au^{198},

(4) comparison of the total β counting rate with the area under the photopeak at 307 keV in a spectrum of Rh^{107} obtained on the multichannel pulse sorter, using calibrated β and γ counters and making appropriate corrections.

In order to obtain γ probabilities from intensity data for the $A=108$ chain, it was necessary to determine the Ru^{108}/Ru^{107} activity ratio. This was done by β counting of a short-lived ruthenium source with a proportional counter and comparing the 21.7-min Rh^{107} component and the shorter-lived (Ru^{107},Ru^{108},Rh^{108}) component, making appropriate corrections.

In the same way, a composite half-period for the (Ru^{107},Ru^{108},Rh^{108}) mixture was obtained. Half-period determinations of such mixtures, as well as the half-period determination of 21.7-min Rh^{107}, were also made by integral counting of ruthenium and rhodium sources using NaI(Tl) crystals. For 16.8-sec Rh^{108}, the half-period was determined by β counting with the 3.8 cm ×5.1 cm Pilot B scintillation plastic, with the discriminator set to reject all pulses corresponding to β rays of energy less than 2.0 MeV. The half-period of Ru^{108} was determined by selectively counting, using absorbers and electronic discrimination, the radiations of Rh^{108} in equilibrium with Ru^{108} in a short-lived ruthenium source.

For determining the mass assignments 107 and 108 for the two decay chains, an early step was to ascertain

[23] L. Grodzins, Rev. Sci. Instr. **26**, 1208 (1955).

whether the palladium isotopes in these chains were radioactive. This was done by evaporating the chloroform from the extract of the palladium-dimethylglyoxime complex, counting the β rays with a gas-flow proportional counter, and comparing the activity with that obtained earlier for the short-lived ruthenium progenitors; a growth time of 35 min was allowed from the counting of the ruthenium source (as RuO_2) to the milking therefrom of the palladium, and the same counting conditions (counter shelf, source mounting, and the like) were employed for the ruthenium and palladium sources.

The mass assignment for the 107 chain was established by determining the mass number of 21.7-min Rh^{107}. This was done by cross bombardments supported by chemical evidence, using the reactions $Ru^{104}(\alpha,p)Rh^{107}$ and $Pd^{108}(n,pn)Rh^{107}$ as follows:

(1) bombardment of natural ruthenium and of isotopically separated Ru^{104} (98.2% Ru^{104}) with alpha particles of various energies from 11.5 to 24.5 MeV, followed by chemical separation of the rhodium activities in the case of bombardments of natural ruthenium with 24.5-MeV alphas;

(2) fast-neutron bombardment of palladium of natural isotopic composition and of separated isotopes Pd^{104}, Pd^{105}, Pd^{106}, Pd^{108}, and Pd^{110}.

The samples were examined in each case for the presence of 21.7-min Rh^{107}, using as the criterion the presence of a 307-keV γ of half-period about 22 min, the γ spectrum being obtained with the 7.6-cm NaI(Tl) crystal and 256-channel pulse sorter. The fast neutrons for (2) were obtained by bombarding targets of beryllium or lithium with 15-MeV deuterons, giving neutrons of maximum energies 18.5 and 30 MeV, respectively. Alpha particles of the desired energies[24] for (1) were obtained by degrading the 30-MeV alpha beam with foils of Dural and either tantalum or niobium, the tantalum or niobium being used to prevent contamination of the ruthenium or Ru^{104} target by 2.55-min P^{30} recoil nuclei from $Al^{27}(\alpha,n)P^{30}$ reactions in the Dural foils. The chemical purification of rhodium activities for (1) was carried out on targets of RuO_2 (natural isotopic composition) by first removing the ruthenium activities by distillation with $HClO_4$ and then precipitating the rhodium activity as $K_3Rh(NO_2)_6$ from the residue.

The mass assignment for the 108 chain is established by the γ-ray data from decay of Rh^{108}, and this will be discussed later. Attempts were made to corroborate the assignment by the reaction $Pd^{108}(n,p)Rh^{108}$, which should have occurred along with the observed $Pd^{108}(n,pn)Rh^{107}$ reaction. However, no γ-ray evidence for Rh^{108} was observed in the resulting activity. An attempt was made to produce the $Pd^{110}(d,\alpha)Rh^{108}$ reaction, using Pd^{110} bombarded with 15-MeV deuterons. Again, the expected activity failed to appear, possibly because of interference from Ag^{110} and an unknown species of half-period about 1.8 min which might be associated with an impurity.

[24] W. A. Aron and B. G. Hoffman, Atomic Energy Commission Report AECU-663, 2nd rev., 1949 (unpublished).

TABLE I. Gamma rays of Ru^{107}, Ru^{108}, Rh^{107}, and Rh^{108}.

Nuclide	Gamma-ray energy, keV[a]	Probability Gamma rays per disintegration[b]
Ru^{107} (4.2 min)	195	0.143±0.012
	370 (coinc 195)	~0.06
	480 (coinc 195)	weak[c]
	860 (coinc 195)	0.07 ±0.02
	930	0.04 ±0.02
	1030	0.04 ±0.015
	1290	0.04 ±0.007
Ru^{108} (4.5 min)	165	0.28 ±0.023
Rh^{107} (21.7 min)	115	0.005±0.002
	285 (coinc 390)	~0.025[c]
	307	0.73 (ref.)
	365 (coinc 307)	~0.015[c]
	390	0.107±0.009
	470	0.010±0.002
	570	0.018±0.002
	675	0.027±0.002
	Sum lines 680, 880, 1140	
Rh^{108} (16.8 sec)	430	0.43 ±0.035
	510[d]	0.10 ±0.026
	620 (coinc 430)	0.22 ±0.039
	Several (unresolved) 800–1100	<0.05 for any one
	1520	0.051±0.010
	2000	≤0.03
	Sum line 1060	
(Ru^{107} or Ru^{108})	21[e]	~0.07
	90 (uncertain)[f]	weak
	265 (uncertain)[f]	weak
(Ru^{107} or Rh^{108})[g]	1830	≤0.04
	2340	very weak
	2470	≤0.02
	2730	very weak
	2900	<0.005

[a] The probable error in the energy values is in general about 2.5%.
[b] Probable errors quoted do not include errors in normalization of Rh^{108} and Ru^{108} to Ru^{107} and of Ru^{107} to Rh^{107}, nor do they include the probable error in the estimate of the probability of the 307-keV γ associated with Rh^{107}. Therefore, the following errors should be applied to all γ probabilities shown above: Rh^{107} 8%, Ru^{107} 22%, Ru^{108} and Rh^{108} 24%.
[c] Observed in coincidences only.
[d] At least 0.067 consists of γ rays fed by β rays of lower energy than those feeding the 620-keV γ. There is a γ-γ coincidence 430 keV-510 keV which seems to have a probability of about 0.04.
[e] Believed to be K x ray of rhodium, tentatively attributed to isomeric transition in Rh^{107}.
[f] These γ rays seem to be absent in β-γ coincidence spectra and, therefore, might be associated with isomerism in Rh^{107} and/or Rh^{108}.
[g] Most of these γ rays are probably associated with decay of Rh^{108}.

RESULTS

Radiations

Beta Spectra

Kurie plots of the singles β spectra of short-lived ruthenium and of 16.8-sec Rh^{108} showed end points of 4500±600 keV, so this value was accepted for the decay energy of Rh^{108}. A β group at about 3200 keV in the short-lived ruthenium spectrum was also discernible, but the energy could not be estimated with accuracy because of Rh^{108} β rays.

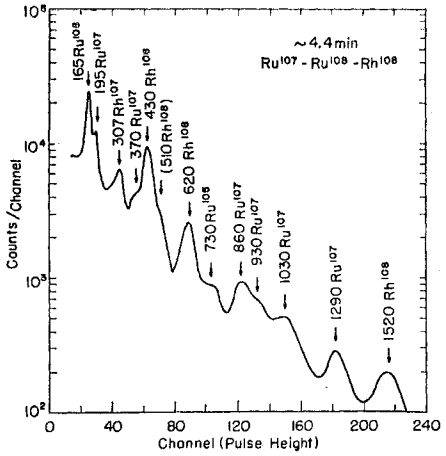

FIG. 1. Pulse-height spectrum of γ rays from fission-product ruthenium (plus daughters). Count taken 9 min after bombardment with 2600 mg/cm^2 absorber at 10 cm from a 7.6×7.6-cm NaI(Tl) detector.

The β spectrum of 21.7-min Rh^{107} gave a Kurie plot with a straight portion, intersecting the axis at 1280 ±150 keV, which is apparently composed of several β groups to excited levels of Pd^{107} as will be seen later, and a higher-energy tail, amounting to perhaps 5 to 10% of the total, which had no straight portion.

In order to obtain decay energies for Ru^{107} and Ru^{108}, it was necessary to resort to β-γ coincidence studies, which also clarified the Rh^{107} situation considerably, and these will be discussed shortly. For completeness we shall anticipate the results by stating that the following total decay energies (keV) were found: Ru^{107} 3150±300, Ru^{108} 1320±100, and Rh^{107} 1510±40.

Gamma-Ray Spectra

Energies and intensities of γ rays associated with the four species are shown in Table I. The accuracy of the reported energy values depends on intensity and other factors, but, in general, is better than 2.5% at a 90% confidence level. Some sample spectra are shown in Figs. 1–4.

The γ rays associated with Ru^{107} were distinguished from those associated with Ru^{108} by varying the bombardment conditions to produce different Ru^{108}/Ru^{107} activity ratios as described earlier (see Experimental). Pile-neutron fission of uranium gave the lowest ratio and 15-MeV deuteron fission of thorium the highest, the two differing by a factor of about 1.5. It was found that the 165-keV γ is associated with Ru^{108} while the 195-, 860-, and 1290-keV γ rays, and probably also the 930- and 1030-keV γ rays, are associated with Ru^{107}. As will be shown later the 930- and 1030-keV γ rays are definitely assignable to Ru^{107} on the basis of β-γ coincidence experiments as are the 370- and 480-keV γ rays.

There is a weak γ ray at 2000±100 keV which is assigned to Rh^{108} on the basis of β-γ coincidence measurements (see later). There are also weak γ rays at 1830±40, 2340±90, 2470±100, 2730±100, and 2900 ±100 keV, any one of which might be associated with either Ru^{107} or Rh^{108} (Ru^{108} has insufficient decay energy). Owing to the low intensities of these γ rays and the difficulty of getting good γ spectra for Rh^{108}, it was not determined which of these are associated with Ru^{107} and which ones are associated with Rh^{108}.

There are also listed in Table I two weak γ rays, 90 and 265 keV, which seem to be associated with Ru^{107} and/or Ru^{108}. However, we cannot be sure that they are not associated with contaminants of some kind, and for this reason they are listed as "uncertain."

The probabilities shown in Table I were calculated as follows:

(1) The probability for the 307-keV peak associated with the decay of 21.7-min Rh^{107} was determined by the several methods described earlier (see Experimental). The probabilities for the other γ rays associated with Rh^{107} were then determined in a Rh^{107} spectrum by comparison with the 307-keV peak.

(2) Knowing the time allowed for growth of Rh^{107} from its 4.2-min Ru^{107} parent at the time a ruthenium spectrum was taken, the measured relative intensities of the Rh^{107} 307-keV peak and the Ru^{107} γ rays in that spectrum were corrected for this growth time to give the probabilities of the latter. The probabilities for the 165-keV γ associated with 4.5-min Ru^{108} and the 430-keV γ associated with its 16.8-sec Rh^{108} daughter were determined in the same way, with additional corrections for the expected difference in fission yield and the difference in half-period between Ru^{107} and Ru^{108}.

(3) The probabilities of the other Rh^{108} γ rays were then determined in a Rh^{108} spectrum by comparison with the 430-keV γ ray.

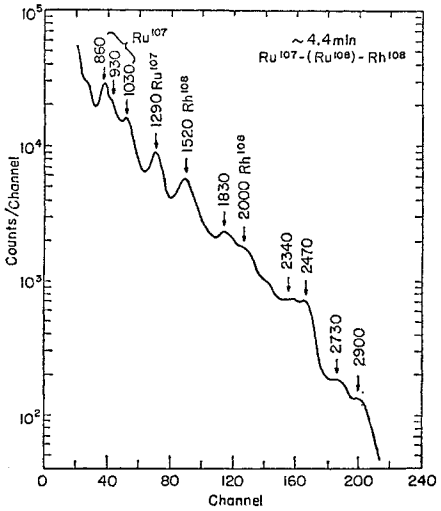

FIG. 2. High-energy γ rays of fission-product ruthenium (plus daughters). Count taken 6 min after bombardment at about 12 cm from a 7.6×7.6-cm NaI(Tl) detector.

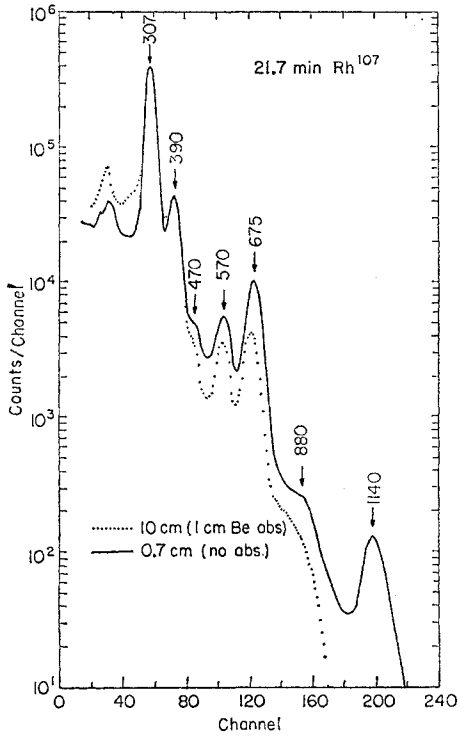

FIG. 3. The γ rays of rhodium milked from fission-product ruthenium 10 min after bombardment, using a 7.6×7.6-cm NaI(Tl) detector.

The best value for the probability of the 307-keV peak associated with the decay of Rh^{107} is 0.75±0.06. It should be noted that the 307-keV peak includes a small contribution from the 285-keV γ, and that the probability 0.73 listed in Table I for the 307-keV γ has been corrected for this contribution.

The uncertainty in the time allowed for growth of Rh^{107}, i.e., the uncertainty in the amount of time elapsed between the final ruthenium separation and the taking of the ruthenium γ spectrum, introduces an error of about ±20% in the probabilities of the γ rays associated with Ru^{107}, Ru^{108}, and Rh^{108}.

The additional corrections for difference in yield and half-period between Ru^{107} and Ru^{108} were made by determining the number of Ru^{107} disintegrations occurring during the accumulation of a spectrum, relative to Ru^{108}. The value 1.3±0.1 was obtained for this number by total β counting (as described in Experimental) of a ruthenium sample prepared in the same way as those from which the spectral analyses were made (15-MeV deuteron fission of uranium). This value agrees with the result (1.3) of calculations based on mass-yield data of Sugihara *et al.*,[25] charge-distribution data and Z_P formulas of Coryell *et al.*,[2] and the measured half-periods (see later) of Ru^{107} and Ru^{108}.

[25] T. T. Sugihara, P. J. Drevinsky, E. J. Troianello, and J. M. Alexander, Phys. Rev. **108**, 1264 (1957).

Beta-Gamma Coincidences

Gating on either the 195- or 860-keV γ rays associated with Ru^{107} showed the spectrum of coincident β rays to have an end point of 2100±300 keV. Consideration of the coincidence relationships and intensity values shown in Table I leads to the conclusion that this β group is a transition to the 1050-keV level of Rh^{107}. Thus, a decay energy of 3150±300 keV is established for Ru^{107}, which is consistent with the weak indication observed in the β singles spectra.

A β group of 1150±100 keV was found to be coincident with the 165-keV γ associated with Ru^{108}. Thus, it is concluded that the decay energy for Ru^{108} is 1320±100 keV.

The following γ-β coincident pairs were found in the decay of Rh^{107} (energies in keV): 675 with 840±40, 570 with 940±60, 390 with 1140±50 and 840±60, and 307 with 1200±50. These data indicate a decay energy of 1510±40 keV for Rh^{107}. Together with the β singles data given earlier, these data qualitatively confirm the observation made by other methods that decay of Rh^{107} leads primarily to excited levels of Pd^{107}. These data also indicate that the 307- and 390-keV γ rays are not in coincidence with each other, and it will be seen shortly that γ-γ coincidence experiments support this indication.

Gating on successively higher-energy portions of the short-lived ruthenium β spectrum (Ru^{107},Ru^{108},Rh^{108}) gave clear confirmation that the 195-, 370-, 860-, 930-, 1030-, and 1290-keV γ rays are all associated with decay of Ru^{107}, as all these γ rays remained visible in γ-ray spectra coincident with β rays of energies sufficiently high that the 165-keV γ associated with Ru^{108} had become indistinguishable. The change in the relative heights of these Ru^{107} γ rays as a function of β energy was not particularly marked and, therefore, it appears as though the β groups feeding the 930-, 1030-,

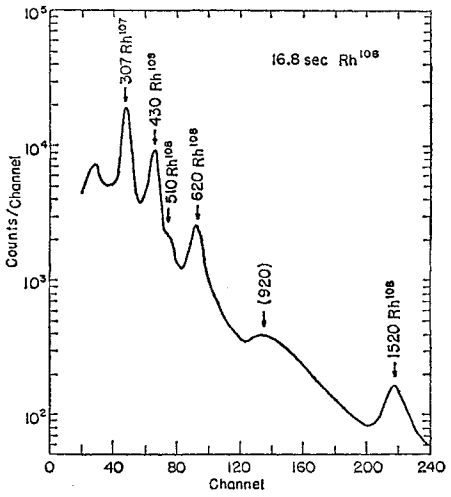

FIG. 4. The γ rays of the short-lived rhodium daughter of 4.4-min fission-product ruthenium. Source counted at 10 cm from a 7.6×7.6-cm NaI(Tl) detector with 2600 mg/cm² absorber.

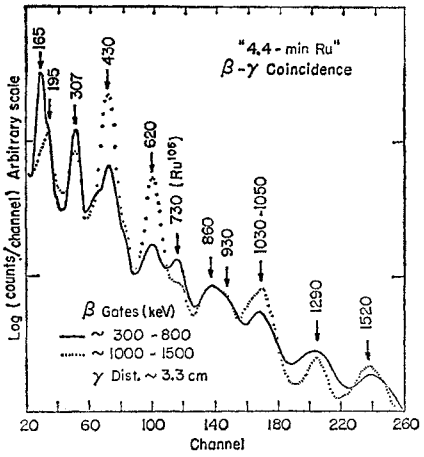

FIG. 5. The γ rays coincident with low- and medium-energy β rays in 4.4-min fission-product ruthenium (plus daughters).

and 1290-keV γ rays must be not greatly different in energy (i.e., not more than 500 keV) from those feeding the 195- and 860-keV γ rays (see Fig. 5). This in turn suggests that the β transitions feeding all these γ rays are transitions to Rh^{107} levels near 1 MeV of excitation.

As the β gate was moved to successively higher energies (Fig. 6), the γ rays associated with Ru^{107} gradually disappeared and the γ rays observed were primarily those associated with Rh^{108} (compare Figs. 1, 2, 4, 5, and 6). It could then be seen that there are γ rays in the region above the 1520-keV γ up to at least 2600 keV which, therefore, must be associated with Rh^{108}. The counting statistics were poor, however, and the only peak which was definitely characterized was at 2060 ± 100 keV, which is assumed to be the same as the 2000-keV peak observed in the singles spectrum. Of the remaining γ rays in this region (1520 to 2600 keV) observed in the short-lived ruthenium spectrum, the majority are probably associated with Rh^{108} since the singles and coincidence spectra are quite similar.

At the same time, the intensity of the 510-keV component fell very rapidly, having disappeared entirely by the time the β gate had been raised to 1900 keV (encompassing 1900 to 3300 keV). As an upper limit, its intensity at this gating energy was no more than 15% that of the 620-keV γ. The latter had fallen only about 25% relative to the 430-keV γ, referred to the Rh^{108} singles spectrum; compare Figs. 4 and 6. Qualitatively, this means that a large fraction of the 510-keV γ component is fed by β groups considerably lower in energy than those feeding the 620-keV γ. Quantitatively, since the 620-keV γ arises from the 1050-keV level of Pd^{108}, it means that 510-keV γ transitions resulting from β transitions directly to the 940-keV level of Pd^{108} occur in less than 3.3% of the Rh^{108} disintegrations. Thus, fewer than one third of the γ rays in the 510-keV components of the Rh^{108} spectrum arise from β transitions to the 940-keV Pd^{108} level. However, some or all of the remainder might still arise from the 940-keV level, fed by γ transitions from higher Pd^{108} levels.

Judging from this upper limit and from the fact that cascade/crossover ratios from second 2+ levels for nuclei in this region are commonly in the neighborhood of 2.0 or more,[26,27] we infer that the β transition to the 940-keV level of Pd^{108} probably occurs in less than 5% of the Rh^{108} disintegrations. This is also supported by the β-γ coincidence experiment. By the time the β gate had reached 1900 keV, the coincident γ spectrum in the region at 940 keV had become rather flat. The height of the continuum was such that, using the 620-keV γ as a reference, we calculate that 940-keV crossover γ rays resulting from direct β transitions to the 940-keV level of Pd^{108} occur in less than 3% of the Rh^{108} disintegrations.

All the γ rays observed in the (Ru^{107},Ru^{108},Rh^{108}) singles spectrum were present in the coincidence spectrum, except the uncertain 265-keV γ and possibly the uncertain 90-keV γ. Therefore, none, except possibly these two, have to do with isomeric transitions.

Gating on successively lower-energy portions of the Rh^{107} β spectrum, the 307-keV γ appeared first (at a β gate about 1050 keV), followed shortly (around 900 keV) by the 390-keV γ, then (around 610 keV) by the 570- and 680-keV γ rays. Continuing to lower energies (around 190 keV) it was seen that all the γ rays observed in the Rh^{107} singles spectrum (except possibly the 115-keV γ, which was not studied in this connection) occur in about the right relative intensities, showing that none of them have to do with isomeric transitions. The valley between the 307- and 390-keV γ rays was deepened by about 70% when gating on high-energy β rays. This is due to the reduction in the intensity of the 365-keV γ component.

Gamma-Gamma Coincidences

All the γ-γ coincidence relationships recorded in Table I were obtained by means of the XYZ Analyzer. The fast-slow coincidence apparatus was used to verify the coincidences 195–370 and 195–860 in decay of Ru^{107}, 307–365 and 390–285 in the decay of Rh^{107} (see later), and 430–510 and 430–620 in the decay of Rh^{108}. The strong coincidences 195–860 in the decay of Ru^{107} and 430–620 in the decay of Rh^{108} were also verified by coincidence summing (by noting the suppression of the component γ rays at high geometrical efficiency and the appearance of appropriate sum lines), and coincidence-sum lines at 680, 880 ± 50, and 1140 in Rh^{107} decay (see Fig. 3) were observed.

We were unable to ascertain what γ rays participate in the cascade from the Pd^{107} level at 1140 keV. The intensity of the sum line is such that the cascade which it represents occurs in only about 0.2% of the Rh^{107} disintegrations, so that we would not necessarily ex-

[26] D. M. van Patter, Nuclear Phys. 14, 42 (1959).
[27] P. H. Stelson and F. K. McGowan, Phys. Rev. 121, 209 (1961).

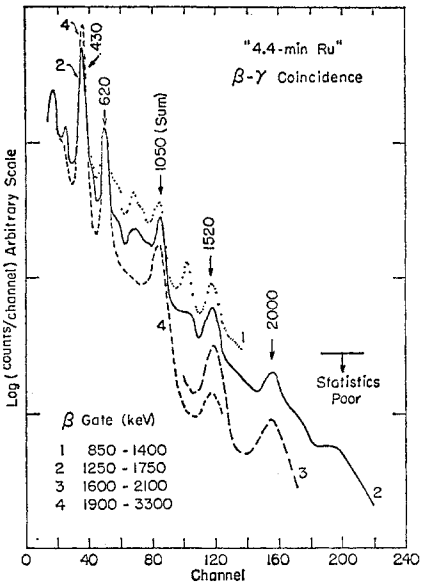

FIG. 6. The γ rays coincident with high-energy β rays in 4.4-min fission-product ruthenium (plus daughters).

pect to be able to detect the weaker member of the cascade in the singles spectrum or to be able to observe the γ-γ coincidence with the fast-slow unit or the XYZ Analyzer. Special efforts were made to find coincidences involving the 470-, 570-, and 675-keV γ rays in the decay of Rh^{107}, using the XYZ Analyzer at low gain for a long exposure time, with negative results. As for the 880-keV sum line in Pd^{107}, its intensity was much too low to permit any information about it to be obtained.

Data from the fast-slow γ-γ coincidence experiments and from the XYZ Analyzer indicate that the intense 307- and 390-keV γ rays in the decay of Rh^{107} are not in coincidence with each other, but rather with 365- and 285-keV γ rays, respectively. These latter two γ rays appear in the singles spectrum only as a slight broadening of the low-energy side of the 307-keV peak and a filling-in of the valley between the 307- and 390-keV peaks. An upper limit for their intensities can be estimated from the singles spectrum and is approximately 0.05 that of the 307-keV γ ray. Using the fast-slow coincidence apparatus and gating on the region 270 to 420 keV in one crystal and 200 to 600 keV in the other, we found the coincidence rate, referred to the singles rate, was 0.8 as great as would be expected if the 307- and 390-keV γ rays were in coincidence with each other. The limits of error would allow this to be taken as evidence that the two are indeed in coincidence; however, gating on the 390-keV γ alone, the observed coincidence rate was only 0.5 as great as would be expected if the 307- and 390-keV γ rays were in coincidence. From these numbers it is calculated that the intensities of the 285- and 365-keV γ rays are, respectively, 0.5 and 0.4 the intensity of the 390-keV γ with an error of $\pm 50\%$ of the stated values. It is then calculated that the aggregate intensities of the 285- and 365-keV γ rays combined is about 3.5 times the intensity of the 675-keV γ; this is contradicted by the sum-coincidence data (Fig. 3), which indicate that the aggregate intensity of the 285- and 365-keV γ rays combined is about equal to, or perhaps slightly greater than, the intensity of the 675-keV γ. In any case, the weakness of the sum line is further confirmation that the 307- and 390-keV γ rays are not in coincidence. The XYZ Analyzer data indicate that the 285- and 365-keV γ rays are of comparable intensity. The XYZ Analyzer data also indicate that the total energies of the two cascades (285- +390-keV and 365- +307-keV) are the same and are equal to 675 ± 30 keV. Sum-coincidence data (Fig. 3), which permit a direct energy comparison between the 675-keV γ ray and the sum line, indicate that the sum-line energy is slightly higher (680 ± 15 keV) than the 675-keV γ, implying that one or both of the cascades and the 675-keV γ might be associated with different levels. Intensity considerations require that the 390- and 307-keV γ rays be the bottom members of the two cascades and, for that matter, that they must both represent transitions to Pd^{107} in the ground level.

Further evidence that the 307- and 390-keV γ rays are not in coincidence with each other is furnished by β-γ coincidence measurements which have already been discussed and by the fact that the height of the 390-keV peak remains essentially constant with respect to the much higher 307-keV peak as the solid angle subtended by the NaI(Tl) crystal is increased (Fig. 3).

An experiment was performed in which were recorded the energies of all γ rays that participate in a fast-coincidence (less than 10^{-7} sec) cascade from a level of Pd^{107} at about 680 keV (by the summing circuit discussed in the previous section). Two broad peaks were observed, at about 300 and 380 keV. Presumably the poor resolution of the apparatus and the poor counting statistics caused a merging of the 285- and 307-keV peaks on the one hand, and the 365- and 390-keV peaks on the other, so that the expected four maxima were not observed. At any rate, the experiment showed that there are probably no other cascades from the neighborhood of 680 keV, as no γ rays below 280 or above 400 keV were observed.

Because the 430–510 coincidence associated with the decay of Rh^{108} is much weaker than the 430–620 coincidence, and because of interference from random 430–430 coincidences and coincidences from the Ru^{105} present, the intensity of the 430–510 coincidence cannot be estimated with great accuracy. Our best estimate from the fast-slow coincidence data is that the 430–510 coincidence involves, very roughly, 40% of the 510-keV γ rays in the Rh^{108} singles spectrum, or about 4% of the Rh^{108} disintegrations. Mainly because no 510–620 coincidence was detected, the 430–510 coincidence is thought to represent the cascade from

the 940-keV Pd^{108} level. A 940-keV crossover intensity compatible with this, judging from the usual cascade/crossover intensity ratio of about 2 commonly observed for second 2+ levels of nuclei such as this, would be about 2% of all Rh^{108} disintegrations. This leads to the estimate that the 940-keV level of Pd^{108} is populated in about 6% of the Rh^{108} disintegrations, though not necessarily by β transitions directly from Rh^{108}.

Coincidences of the 1520-keV γ in the decay of Rh^{108} were sought in the XYZ Analyzer presentation and by coincidence summing, but none were found.

Conversion Electrons, X rays, and the Question of Isomerism

The region from 100 keV upwards was examined for conversion electrons in these four species but none were found, indicating that conversion electrons in this energy region do not occur in more than 15% of the disintegrations of Ru^{107} or Ru^{108}.

A 21-keV γ of half-period about 4.5 min, presumably the K x ray of ruthenium, rhodium, or palladium, appears in the short-lived ruthenium spectrum. Its intensity corresponds to about 5 to 8% of the Ru^{107} disintegrations. The x ray was not observed in the rhodium milked rapidly from ruthenium. At the same time it should be recalled that β-γ and γ-γ coincidence relationships are such that none of the γ rays visible in the short-lived ruthenium singles spectra corresponds to isomeric transitions (half-period more than 10^{-7} sec), except possibly the uncertain 95- and 265-keV gamma rays. Thus, it is possible to say that the K-shell conversion coefficient α_K is at least 1.3 for the transition giving rise to the x ray, using the data of Broyles *et al.*[28] to correct for K-shell fluorescence yield. With the minimum allowance for conversion of higher shells, it is possible to say that the total probability of the transition associated with the x ray is at least 0.08 relative to the Ru^{107} disintegrations (or 0.10 relative to the Ru^{108} disintegrations). Since we did not measure L x rays or conversion electrons below 100 keV, no upper limit can be set for the probability of the transition. It is concluded that this transition is a highly converted isomeric transition of energy greater than the K-shell binding energy of the relevant atom (ruthenium, rhodium, or palladium). If the transition occurs in Rh^{107}, Rh^{108}, Pd^{107}, or Pd^{108}, its half-period must be under 10 sec. If it occurs in Ru^{107} or Ru^{108} its half-period must be indistinguishable from that of the ground-level species, that is to say 4 to 5 min, provided that the isomeric level is formed relatively weakly in fission, i.e., provided that the total intensity of the isomeric transition is low. If the isomeric level is formed relatively strongly in fission, i.e., if the intensity of the isomeric transition is sufficiently great that it constitutes the sole or primary mode of formation of the Ru^{107} or Ru^{108} ground state, then the half-period of the isomer is 4.2 min (Ru^{107}) or 4.5 min (Ru^{108}) and the half-period of the ground-state species is somewhat shorter.

Unfortunately it was impossible to determine, by varying the Ru^{107}/Ru^{108} ratio, which mass number is primarily associated with the x ray, because the rhodium K x ray from the highly converted Rh^{105} isomeric transition interferes. However, it is quite unlikely that the x ray is associated with the 108 chain. Isomerism probably does not exist in Ru^{108} and Pd^{108}. Isomerism in Rh^{108} is expected to occur, but not in decay of Ru^{108}, because Ru^{108} presumably has a 0+ configuration and its decay will consequently not reach two Rh^{108} levels differing widely in angular momentum, especially since the γ cascades which might enable this to happen are not present in the decay of Ru^{108}. We tentatively assign the x ray to a short-lived (less than 10 sec) isomeric transition in Rh^{107} formed in the decay of 4.2-min Ru^{107}.

It is possible that the transition is from an isomer in Ru^{107}, of half-period about 4 to 5 min, to a 4.2-min ground-state species, or from an isomer in Ru^{107}, of half-period 4.2 min, to a somewhat shorter-lived ground-state species. It is also possible that the transition is from an isomer in Pd^{107}, other than the already-known 21-sec isomer,[29] reached via β decay from a short-lived Rh^{107} species isomeric with 21.7-min Rh^{107}.

Only a weak (probability$\sim$0.002) x ray could be detected in the spectrum of 21.7-min Rh^{107}, and none could be detected in old rhodium milkings. The β-γ and γ-γ coincidence relationships showed that none of the γ rays associated with 21.7-min Rh^{107} corresponds to an isomeric transition, except possibly the very weak 115-keV γ, and no γ or decay-curve evidence for any radioactive Ru^{107} and Ru^{108} descendants, either long- or short-lived, other than 21.7-min Rh^{107} and 16.8-sec Rh^{108}, could be found. For these reasons it seems probable that (1) the 21.7-min Rh^{107} and 16.8-sec Rh^{108} are ground-level species, and that (2) no measurable portion of the disintegrations of either of them leads to isomeric transitions in Pd^{107} or Pd^{108}. The 21-sec Pd^{107} isomer is not formed in Rh^{107} decay.

In summary on the question of isomerism, there is probably an isomer of Rh^{107} formed in Ru^{107} decay but no other isomers formed in Ru^{107} or Ru^{108} decay.

Half-Periods

The half-period of the mixture of Ru^{107} and Ru^{108} (with Rh^{108} in equilibrium) was measured to be 4.35 $\pm$0.2 min. The half-period of Ru^{108} alone was measured for over eleven half-periods to be 4.5$\pm$0.2 min. By measuring the difference in peak heights of the 165- and 195-keV γ rays as a function of time, it was observed that the half-period of Ru^{107} is 0.4$\pm$0.2 min

[28] C. D. Broyles, D. A. Thomas, and S. K. Haynes, Phys. Rev. **89**, 715 (1953).

[29] U. Schindewolf, Phys. Rev. **109**, 1280 (1958).

shorter than that of Ru^{108}. Our best estimates of half-periods based on the above data are 4.2 ± 0.3 min for Ru^{107} and 4.5 ± 0.2 min for Ru^{108}.

The half-period of Rh^{107} was measured for a duration of eight half-periods to be 21.7 ± 0.4 min. The half-period of Rh^{108} was measured to be 16.8 ± 0.5 sec, using the analyzer as multiscaler with 0.60 sec per channel and computer analysis.

Mass Assignments

General. We confirm earlier reports[5,7] that the palladium descendants of the two short-lived ruthenium species are inactive. The activity of the palladium sample milked from short-lived ruthenium was of the order of 10^{-3} of what it would have been if 13.6-h Pd^{109} were formed, and similarly for 22-min Pd^{111} and 21-h Pd^{112}. Thus, neither of the $\sim$4-min ruthenium activities has mass number 109, 111, or 112.

We take average[9,30] predicted total decay energies (MeV) as: 3.26 for Ru^{107}, 1.56 for Rh^{107}, 1.40 for Ru^{108}, 4.72 for Rh^{108}, 2.64 for Ru^{110}, 5.99 for Rh^{110}. These indicate that the two short-lived ruthenium isotopes (decay energies about 3.2 and 1.3 MeV) are Ru^{107} and Ru^{108}, and that their 21.7-min and 16.8-sec daughters (decay energies about 1.5 and 4.5 MeV) are Rh^{107} and Rh^{108}.

21.7-min Rh^{107}. A 22-min 307-keV γ ray was emitted by fast-neutron activated samples of palladium of natural isotopic composition and Pd^{108}, but not any other activated palladium isotopes. Results of fast-neutron bombardments of Pd^{104} and Pd^{106} indicate that (n,p) reactions are not taking place to any great extent, which is perhaps not surprising[31–33] and that $(n,p2n)$ reactions do not have a high probability compared to (n,pn). On the other hand, products of $(n,2n)$ and (n,γ) reactions with Pd^{108} are well characterized. Thus, one may infer that the species has been produced by the reactions $Pd^{108}(n,pn)Rh^{107}$, and $Pd^{108}(n,d)Rh^{107}$.

No 22-min 307-kev γ was distinguishable in the profusion of γ rays from natural ruthenium samples which had been bombarded with 14-MeV alpha particles. However, bombardment of Ru^{104} with 14.4-MeV alpha particles gave rise to an intense 307-keV γ of 22-min half-period. Further bombardments of Ru^{104} with alpha particles of energies 11.5 and 12.2 MeV indicated that the species responsible for this γ is produced at a minimum alpha particle energy of about 12 MeV. Reactions on Ru^{104} that are expected to become observable at about this energy are (α,α'), (α,γ), (α,n), (α,p), and possibly $(\alpha,2n)$. Of these, all but (α,p) lead to products already well characterized, and only (α,p) produces a rhodium isotope. When the species was produced by bombardment of Ru^{104} with 24.5-MeV alphas, the 390-keV γ of Rh^{107} was visible as well as the 307-keV γ, and in about the correct relative intensity.

Sources of rhodium, prepared by chemical separation from RuO_2 of natural isotopic composition bombarded with 24.5-MeV alpha particles, emitted a 22-min 307-keV γ, partially masked by the 320-keV γ rays of 36-h Rh^{105} from the reaction $Ru^{102}(\alpha,p)Rh^{105}$. The relative intensities of the two γ rays on different runs were such as to show that the 22-min 307-keV peak was produced by an isotope of rhodium and not by a contaminant.

These data show the mass number of the 21.7-min rhodium, and therefore the ruthenium precursor, to be 107.

16.8-sec Rh^{108}. From Coulomb excitation[27,34,35] of Pd^{108} and from studies[36–40] of the electron-capture decay of 2.3-min Ag^{108} and of $\geq$5-yr Ag^{108m}, it is known[3,4] that Pd^{108} (ground state 0+) has levels (keV) of 2+ at 427, 2+ at 940, 4+ at 1050, and 0+ at 1050. The decay of the 16.8-sec rhodium involves emission of 510- and 620-keV γ rays in coincidence with a more intense 430-keV γ but not with each other, indicating levels of the palladium daughter nucleus at 0, 430, 940, and 1050 keV. This is taken to be sufficient proof that the 16.8-sec rhodium, and, therefore, its ruthenium precursor, is of mass number 108.

Other Decay Properties

21.7-min Rh^{107}. The data indicate that Rh^{107} decays by β transitions to Pd^{107} in the following levels (keV): 1140 (probable), about 0.2%, $\log ft$ about 5 to 6; 675 (may be two or more levels), 7%, $\log ft=5.4$; 570, 2%, $\log ft=6.2$; 470, 1%, $\log ft=6.5$; 390, 8%, $\log ft=5.8$; 307, 71%, $\log ft=4.8$; and ground level, 0 to 17%, $\log ft\geq6.0$. (The $\log ft$ values were derived from Moszkowski's figures.[41]) The levels at 307 and 390 seem to be fed in comparable amount by cascades from the 675 level, the sum of the probabilities for these cascades being of the same order as the probability for the 675 crossover (see Fig. 7).

It was concluded earlier that decay of Ru^{107} forms not only this 21.7-min species, but probably also a short-lived Rh^{107m} which decays to 21.7-min Rh^{107} by isomeric transition. One expects[4] to have isomers

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[39] E. G. Funk, Jr., G. C. Martin, R. C. Pilger, Jr., and J. W. Mihelich, Bull. Am. Phys. Soc. **6**, 428 (1961).
[40] O. C. Kistner and A. W. Sunyar, Bull. Am. Phys. Soc. **7**, 342 (1962).
[41] S. A. Moszkowski, Phys. Rev. **82**, 35 (1951).

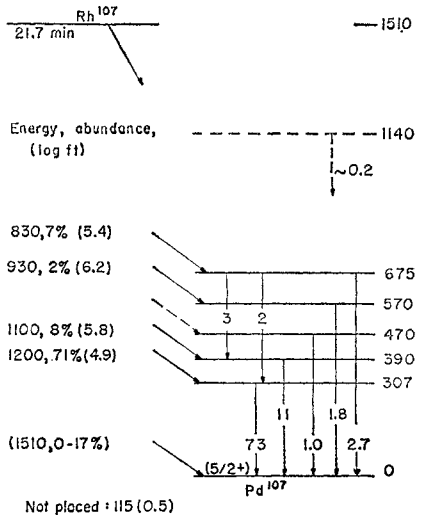

FIG. 7. Proposed decay scheme for Rh^{107}. The γ probabilities are given in % of total decays. Lines representing β transitions are dashed unless actually observed.

of configurations $\frac{7}{2}+$ and $\frac{1}{2}-$, corresponding, respectively, to $(g_{9/2}{}^{3,5,\text{ or }7})_{7/2}$ and $p_{1/2}$ proton states, connected by an $E3$ isomeric transition. It is difficult to predict which of the two should be the lower; although reviews of the subject of isomerism[42,43] have shown that the separation of isomeric levels varies in a systematic fashion with Z and N, the trend indicated by Rh^{103} and Rh^{105} (which would have the $\frac{7}{2}+$ level fall some 100 to 300 keV below the $\frac{1}{2}-$ level) is just the reverse of the well-established trend in the odd-A silver isotopes[4,44] (in which the energy of the $\frac{7}{2}+$ level is commonly the higher of the two and comes to a maximum, relative to the $\frac{1}{2}-$ level, at $N=60$ or 62).

If we take it for granted that the isomeric transition is $E3$, and if α_K for this transition is at least 1.3 as earlier concluded, then the energy of this transition cannot be greater than 150 keV, according to calculations made with the aid of Rose's tables.[45,46] If the isomeric transition has a lower multipolarity, as could be the case if there were a stopover level between the $\frac{1}{2}-$ and $\frac{7}{2}+$ levels, then the maximum energy is somewhat less than 150 keV for $\alpha_K \geq 1.3$.

For $E3$ transitions of energy less than 150 keV, taking conversion in L and M shells into account, the minimum isomeric transition probability for the K x-ray intensity corresponds to 0.13 of the Ru^{107} disintegrations. Below 100 keV this minimum probability rises rapidly and reaches 1.0 at about 42 keV. If the isomeric transition is of multipolarity lower than $E3$, then the probability of the isomeric transition may be as low as 0.08 of the Ru^{107} disintegrations as stated earlier.

Thus, we arrive at the tentative conclusion that 8 to 100% of the Ru^{107} disintegrations form a Rh^{107} isomer of half-period less than 10 sec which undergoes a highly converted ($\alpha_K \geq 1.3$) isomeric transition of energy between 25 and 150 keV to the ground-level Rh^{107}.

Even though it is not possible to predict the energy separation between the two isomeric Rh^{107} levels, it would be desirable to know which of the two, $\frac{7}{2}+$ or $\frac{1}{2}-$, is the lower. Since the 21.7-min species is undoubtedly the ground-level Rh^{107} isomer, the problem becomes a matter of determing the spin of that species. Unfortunately, we cannot make such a determination from our data. The ground level of Pd^{107} is probably a $\frac{5}{2}+$ level,[4] presumably the effect of an odd $d_{\frac{5}{2}}$ neutron; therefore, if 21.7-min Rh^{107} were $(g_{9/2}{}^{2n+1})_{7/2}$, then the β transition between the two ground levels would be a l-forbidden transition ($\Delta I=1$, $\Delta l=2$, $\log ft=6$ to 9), which is not inconsistent with the data. On the other hand if 21.7-min Rh^{107} were $p_{1/2}$, then the beta transition to Pd^{107} in the $\frac{5}{2}+$ ground level would be unique first forbidden ($\Delta I=2$, parity change, $\log ft$ about 9), which again is not inconsistent with the data. Thus, we have no good evidence about the problem just posed, but, as will be seen shortly, we tend to favor $\frac{7}{2}+$ rather than $\frac{1}{2}-$ for the Rh^{107} ground level.

The low intensity of rhodium K x rays in the Rh^{107} spectrum indicates that the 307-keV transition must be of either the $E1$ or $M1$ type. Therefore, a $\frac{5}{2}+$ ground level for Pd^{107} implies $\frac{3}{2}\pm$, $\frac{5}{2}\pm$, or $\frac{7}{2}\pm$ for the 307-keV Pd^{107} level. The beta transition from Rh^{107} to this level is probably of the allowed ($\Delta I=0$ or 1, $\Delta l=0$, $\log ft=4$ to 6) type, suggesting $\frac{5}{2}+$ or $\frac{7}{2}+$ (if Rh^{107} is $\frac{7}{2}+$) or $\frac{3}{2}-$ (if Rh^{107} is $\frac{1}{2}-$) for this level.

In order that a β-γ or γ-γ coincidence appear in the fast-slow coincidence experiments, the lifetime of the intermediate level must be of the order of or less than the resolving time of the apparatus. Consideration of the Weisskopf estimate[47] of γ half-periods for single-particle transitions (correcting for conversion and for the discrepancies[48] between the Weisskopf-estimate values and the lifetimes normally observed) allows limits to be placed on the multipolarities of γ transitions. For the 390-keV transition in Pd^{107}, such considerations indicate $E1$, $M1$, or $E2$ character, which, in turn, indicate $\frac{1}{2}+$, $\frac{3}{2}\pm$, $\frac{5}{2}\pm$, $\frac{7}{2}\pm$, or $\frac{9}{2}+$ for the 390-keV level. The $\log ft$ of 5.8 for the β transition to

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this level from Rh^{107} excludes all possibilities but $\frac{5}{2}+$, $\frac{7}{2}+$, and $\frac{9}{2}+$ (assuming $\frac{7}{2}+$ for Rh^{107}) or $\frac{3}{2}-$ (assuming $\frac{1}{2}-$ for Rh^{107}).

The β transitions to the 570- and 670-keV levels of Pd^{107} are almost certainly first forbidden ($\Delta I=0$ or 1, parity change, $\log ft=6$ to 8), l-forbidden, or allowed. Thus, $\frac{5}{2}\pm$, $\frac{7}{2}\pm$, or $\frac{9}{2}\pm$ (assuming $\frac{7}{2}+$ for Rh^{107}), or $\frac{1}{2}\pm$ or $\frac{3}{2}\pm$ (assuming $\frac{1}{2}-$ for Rh^{107}) is indicated for these levels; β-γ coincidence data are consistent with all these possibilities except perhaps $\frac{1}{2}-$. There may be two or more close-lying levels at 670 to 690 keV, but the $\log ft$ values would then be in the neighborhood of 5.6 to 6.0, thus, indicating the same choice of angular momentum and parity.

The Pd^{107} levels just discussed present a trying situation for the strict single-particle shell model,[49–51] as only a few single-particle levels would be expected at low enough energies to be formable by Rh^{107} decay, namely $d_{5/2}$, $g_{7/2}$, $d_{3/2}$, $s_{1/2}$, and $h_{11/2}$ (the 21-sec Pd^{107} isomer is thought[27] to represent the $h_{11/2}$ single-particle level). Much better success can be had with the unified model approach,[52–56] in which Pd^{107} is regarded as having a Pd^{106} core undergoing collective motions which are coupled in various ways to the odd neutron. This approach is useful because the level scheme of Pd^{106} has been extensively studied[57–61] and interpreted in terms of collective motions. Adding the odd neutron to the Pd^{106} core will give, for the lowest excited levels of the Pd^{107} thus formed, the single-particle states of the odd nucleon, and levels formed by coupling the odd nucleon in its ground state to the levels of the core. We assume that the odd particle is coupled weakly to the even-even core so that its addition does not greatly change the core shape. For approximating Pd^{107} we form a $\frac{5}{2}+$ ground level by coupling the odd neutron in its ground state ($d_{5/2}$) with the ground state of the core (0+), and we form two quintets ($\frac{1}{2}+$, $\frac{3}{2}+$, $\frac{5}{2}+$, $\frac{7}{2}+$, $\frac{9}{2}+$) taking the $d_{5/2}$ neutron and the first two 2+ states of the core, a multiplet ($\frac{3}{2}+$, $\frac{5}{2}+$, . . . , 13/2+) with the $d_{5/2}$ neutron and the first 4+ state of the core, and a $\frac{5}{2}+$ level with the $d_{5/2}$ neutron and the second 0+ state of the core, and so forth. Not far above the ground level, if the 21-sec level is the $h_{11/2}$ single-particle level, there will be singlets (11/2−) and multiplets based on a $h_{11/2}$ odd neutron and so forth with other single-particle neutron states. Obviously this approach provides enough even-parity levels in Pd^{107} to accommodate our data on the assumption of $\frac{7}{2}+$ for Rh^{107}; it is not so successful if $\frac{1}{2}-$ is assumed for Rh^{107}, for then several low-spin odd-parity Pd^{107} levels are needed.

4.2-min Ru^{107}. The intensity of the 195-kev γ associated with the decay of Ru^{107} is greater than the sum of the intensities of all the γ rays in coincidence with it (cf. Table I). Therefore, it seems probable that the 370-, 480-, and 860-keV γ rays feed the 195-keV γ. However, it can be seen in Table I that the intensity errors are such that the reverse situation is also possible, i.e., that the 195-keV γ feeds the other three. This situation would require that the 370-keV γ in turn feed another γ transition or cascade of at least equal intensity and appropriate energy (490 keV). The 370-keV γ clearly does not do this. [One can bar the possibility that it might be feeding a Rh^{107m} isomeric level because either (1) the isomeric transition energy would be 490 keV, in which case the unconverted transitions definitely would have been observed; or (2) the isomeric transition energy would be less than 490 keV, in which case the γ fed by the isomeric transition would have been observed.] Therefore, the 195-keV transition is thought to follow the coincident 370-, 480-, and 860-keV transitions.

Thus, it is concluded that there are Rh^{107} levels at 195, 565, and 1050 keV above either the ground level or the isomeric level (the intensity of the isomeric transition could be greater than the sum of all the γ intensities). Because of the intensity balance, and also because of the results of the β-γ coincidence experiments, the 195-keV level is believed to be populated primarily by the γ transitions from the 565- and 1050-keV levels rather than by β transitions. The existence of a level at 675 keV is questionable because the coincidence experiments, although showing a 195–480 coincidence, do not exclude the possibility of a 480–860 coincidence also. The 1030-keV γ is taken to be the crossover transition from the 1050-keV level to the ground (or isomeric) level.

From the foregoing considerations it is inferred that Ru^{107} decays by β transitions to Rh^{107} in the following levels (keV): 1290, 4%, $\log ft=6.3$; 1050, 11%, $\log ft=6.0$; 930, 4%, $\log ft=6.6$; 675 or 1530, $<5\%$; 565, $\sim 6\%$, $\log ft\sim 6.7$; 195, 0 to 5%, $\log ft\geq 7.0$; ground and/or isomeric level 74%, $\log ft=5.9$ (it is

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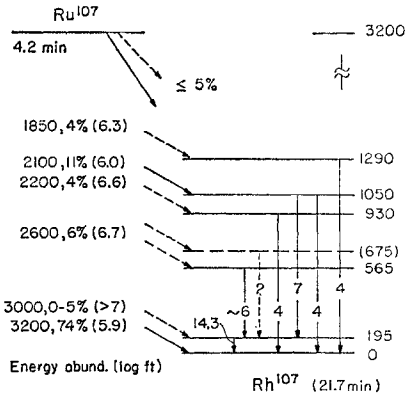

FIG. 8. Proposed decay scheme for Ru^{107}. The γ probabilities are given in % of total decays.

probable that only one of the two expected Rh^{107} isomers is formed appreciably by direct β transitions from Ru^{107}). In this listing it is understood that (1) it is possible that the energy of the supposed Rh^{107m} isomeric level should be added to the level called 195 keV, in which case it must be added to the levels 565, 675 or 1530, and 1050 keV, and/or (2) that it should possibly be added to any or all of the levels 0, 930, and 1290 keV (see Fig. 8).

It is possible that the 195-keV level is the analog in Rh^{107} of the $\frac{7}{2}+$ or $\frac{1}{2}-$ isomeric level of Rh^{105} or Rh^{103} but that it undergoes a fast low-multipole transition (195 keV) to a level intervening between the $\frac{7}{2}+$ and $\frac{1}{2}-$ levels. The ensuing isomeric transition would then be of multipolarity less than $E3$ and having energy, half-period, and α_K commensurate with our observations but not analogous to the isomeric transitions in Rh^{103} or Rh^{105}.

For Ru^{107} the neutron number N is 63. According to the shell model,[49,50] the order of filling of subshells after the $N=50$ shell closure is, for neutrons, $2d_{5/2}$, $1g_{7/2}$, $3s_{1/2}$, $2d_{3/2}$, $1h_{11/2}$, with the reservation that *pairs* of neutrons tend to go into the high-angular-momentum subshells (i.e., $g_{7/2}$ and $h_{11/2}$). For even-Z odd-N nuclei the result is that $\frac{5}{2}+$ ground levels, interpreted to be $d_{5/2}$ neutron states, are observed in nearly all cases from $N=51$ through $N=63$ and then, after the supposed closure of the $d_{5/2}$ and $g_{7/2}$ subshells has been accomplished at $N=64$, $s_{1/2}$ ground levels appear at $N=65$ and persist with few exceptions to $N=75$; there is no evidence for $d_{3/2}$ until $N=71$ (Sn^{121}), none for $h_{11/2}$ until $N=75$ (Sn^{125}), and none for $(d_{5/2}{}^3)_{3/2}$ at all.

However, present data for the even-Z nuclei Pd^{101} ($N=55$), Pd^{103} ($N=57$), and Sn^{111} ($N=61$) suggest that they have $\frac{7}{2}+$ configurations. This implies that many of the $\frac{5}{2}+$ nuclides between $N=53$ and $N=61$ inclusive might be wholly or partly many-neutron $(g_{7/2}{}^{2n+1})_{5/2}$ states rather than $d_{5/2}$ states and that $g_{7/2}$ ground states may appear at $N=63$. Also, there are two nuclides with $N=63$ (Cd^{111} and Sn^{113}) which seem[4] to be $s_{1/2}$.

Thus, the following possibilities suggest themselves for Ru^{107}: $g_{7/2}$, $d_{5/2}$, and $s_{1/2}$. If Ru^{107} decays mainly to a $p_{1/2}$ isomer of Rh^{107}, then $s_{1/2}$ is indicated for Ru^{107} by the logft value. On the other hand, if Ru^{107} decays mainly to the $(g_{9/2}{}^{2n+1})_{7/2}$ isomer of Rh^{107}, then Ru^{107} should be $d_{5/2}$ or $g_{7/2}$, the transitions to Rh^{107} then being of the l-forbidden or allowed types, respectively.

A major factor in deciding among these possibilities is the fact that Ru^{107} behaves quite differently from Ru^{103} and Ru^{105}, in that nearly all the Ru^{103} and Ru^{105} disintegrations proceed by β transitions to excited states of their rhodium daughters,[3,4,13–16,18] which is clearly not the case for Ru^{107} decay. This means that β transition of Ru^{107} to one or the other of the two isomers $(\frac{7}{2}+, \frac{1}{2}-)$ of the rhodium daughter is less hindered than in the cases of Ru^{105} and Ru^{103} decay. One possible explanation for this is that Ru^{103} and Ru^{105} are both $\frac{5}{2}+$, as is commonly believed,[3,4,15] whereas Ru^{107} might be $g_{7/2}$ or $s_{1/2}$ (decaying mainly to the $\frac{7}{2}+$ isomer of Rh^{107} if Ru^{107} is $g_{7/2}$, or to the $\frac{1}{2}-$ isomer if Ru^{107} is $s_{1/2}$). Another possible explanation is that Ru^{103}, Ru^{105}, and Ru^{107} all are $d_{5/2}$ but that the pronounced difference in detailed nuclear configuration which has been suggested[15] as an explanation for the suppression of the l-forbidden β transition of Ru^{105} $(\frac{5}{2}+)$ to the $\frac{7}{2}+$ isomer of Rh^{105} (or of Ru^{103} to the $\frac{7}{2}+$ isomer of Rh^{103}) does not exist between Ru^{107} and the $\frac{7}{2}+$ isomer of Rh^{107}.

The β-γ and γ-γ coincidence data indicate the following multipolarities for the γ rays associated with decay of Ru^{107}: 195 keV, $E1$, $M1$, or $E2$; 380, 860, 930, 1030, and 1290 keV, $E1$, $E2$, $M1$, or $M2$ (1290 possibly $E3$).

16.8-sec Rh^{108}. From the probabilities of the Rh^{108} γ rays listed in Table I, it is calculated that Rh^{108} decays to Pd^{108} as follows: To 1050-keV (0+) level 22%, logft=5.5; to 940-keV (2+) level <5%, log$ft\geq$6.0; to 430-keV (2+) level ~17%, logft~5.9; and to the ground (0+) state 51%, logft=5.5 (see Fig. 9). Thus,

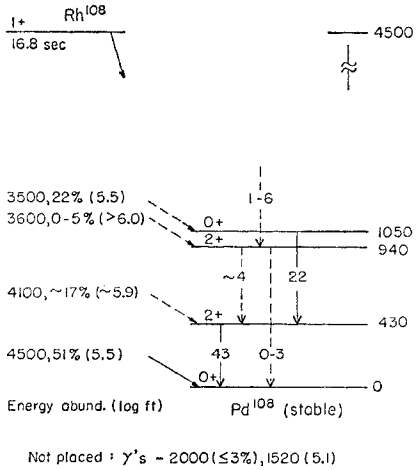

FIG. 9. Proposed decay scheme for Rh^{108}. The γ probabilities are given in % of total decays.

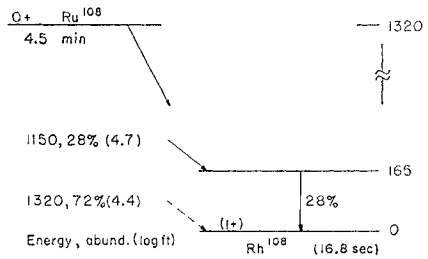

FIG. 10. Proposed decay scheme for Ru^{108}.

all these transitions are of the allowed type [except perhaps the transitions to the 940-keV level; failure to populate this level is noted also[36–38] in decay of 2.3-min $Ag^{108}(1+)$], indicating a 1+ configuration for Rh^{108}. It should be pointed out that it is not necessary to rely on the γ probabilities in order to arrive at this assignment; the relative intensities suffice to show that the Rh^{108} β transitions to the 1050- and 430-keV levels of Pd^{108} are of the same type, and the β transition from Ru^{108} (0+) to ground-level Rh^{108} is of the allowed type (see later), so that a 1+ assignment is indicated even if the γ probabilities reported for Rh^{108} are in error.

The 1+ assignment for Rh^{108} is in harmony with the shell model[49–51] together with Nordheim's strong rule[62] for j-j coupling (according to which the 1+ configuration is due to a coupling of the form $\pi g_{9/2}\nu g_{7/2}$, where π denotes proton, ν denotes neutron). It follows naturally from the rules of Gallagher and Moszkowski[63] based on spin-spin coupling and an asymptotic-quantum-number description of particle states. It is also predicted for j-j coupling by Brennan and Bernstein,[64] according to whom the 1+ ground level would be regarded as arising from a coupling of the form $\pi(g_{9/2}{}^5)_{7/2}\nu d_{5/2}{}^{-1}$ which should produce a 6+ level as well, in close competition.

Other odd-odd nuclei of Z from 45 to 49 which have N from 59 to 69 that have been studied to date, with the exceptions $Ag^{112}(2-)$, In^{108} (2+), and In^{110} (2+),[49,51] all apparently have 1+ ground levels following Nordheim's rules, a coupling of the form $\pi g_{9/2}\nu g_{7/2}$ being assumed. Then Ag^{112}, In^{108}, and In^{110} are regarded as minor failures of the model. However, this assumed coupling ($\pi g_{9/2}\nu g_{7/2}$) ignores the fact that $\pi(g_{9/2}{}^{2n+1})_{7/2}$ and $\nu d_{5/2}$ states are the rule for the neighboring odd-A nuclides. The Brennan-Bernstein approach,[64] on the other hand, predicts the ground levels of odd-odd nuclei from the proton and neutron configurations of their odd-A neighbors, making use of three coupling rules similar to Nordheim's rules but more specific. Using this approach, Ag^{112}, In^{108}, and In^{110} are correctly predicted; however, the model fails for Rh^{104m_2}, and forcing is required for In^{112}, In^{114}, and In^{116}. Otherwise the model performs well in this region, and it is gratifying that Rh^{108} follows the rules.

The decay of Rh^{108} shows levels of Pd^{108} not heretofore observed, and these will now be discussed briefly. Those levels observed by us which have the most immediate bearing upon current collective models,[65–72] namely the 430-, 940-, and 1050-keV levels, are already known. It suffices to say that these levels are in accord with the "near-harmonic" model of Scharff-Goldhaber and Weneser,[65] which predicts a first excited level of configuration 2+, with a (0+, 2+, 4+) triplet at slightly more than twice the energy of the first excited level.

The γ at 1520 keV indicates a level at 1520 keV or higher in Pd^{108}. In any case the β transition to this level from Rh^{108} is probably allowed ($\log ft \leq 5.9$), indicating 0+, 1+, or 2+ for it.

The 2000-keV γ probably originates from a level of spin $I=0$, 1, or 2 since the β transition to it seems to have a $\log ft$ value low enough (≤ 6.5) to exclude $\Delta I > 1$. Whether it is a transition to the ground level cannot be determined.

It was concluded earlier that decay of Ru^{108} probably cannot lead to isomerism in Rh^{108}. This is not to say, however, that we have any evidence against the existence of a high-spin Rh^{108} isomer. The existence of such an isomer, although not formed in Ru^{108} decay, is suggested by the appearance of analogous species in many even-A silver and rhodium isotopes, as well as by the predictions of all of the shell models[49–51,62–64] discussed earlier.

4.5-min Ru^{108}. This nucleus (undoubtedly 0+) decays to Rh^{108} as follows: To 165-keV level 28%, $\log ft = 4.7$; and to ground (1+) level 72%, $\log ft = 4.4$. Apparently the 165-keV level of the Rh^{108} daughter is a 0+ level or another 1+ level (see Fig. 10). No precedent for a 0+ or second 1+ level is known among the neighboring analogous nuclides, and such a situation certainly is not anticipated by use of Nordheim's rules.[62] However, following the Brennan-Bernstein rules,[64] couplings of the forms $\pi(g_{9/2}{}^5)_{7/2}\nu d_{5/2}{}^{-1}$ and $\pi(g_{9/2}{}^{-3})_{7/2}\nu d_{5/2}{}^{-1}$ would each give (1+, 6+) doublets; and couplings $\pi(g_{9/2}{}^5)_{7/2}\nu g_{7/2}{}^{-1}$ and $\pi(g_{9/2}{}^{-3})_{7/2}\nu g_{7/2}{}^{-1}$ would each give (0+, 7+) doublets. (Other levels expected on the basis of these rules are 2− from $\pi p_{1/2}\nu d_{5/2}{}^{-1}$ and 4− from $\pi p_{1/2}\nu g_{7/2}{}^{-1}$.) Thus, a 0+ or

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second 1+ excited level in Rh^{108} would not be inconsistent with the predictions of these latter coupling rules.

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Compound Nucleus Formation Mechanisms in Reaction of Heavy Ions with Medium-Mass Elements

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Excitation functions and range distributions of heavy products formed by the reaction of O^{16}, N^{14}, and C^{12} with Mn^{55} and Co^{59} have been measured. Results show that the bulk of products, with mass numbers greater than that of the target, are formed exclusively by decay of a compound nucleus formed by complete fusion of target and projectile. One nuclide, Cu^{61}, can also be formed from O^{16} bombardment of Co^{59} (but not from the formally similar compound system $Mn^{55}+Ne^{20}$) by a mechanism in which only part of the momentum of the projectile is transferred. It appears to be representative of products with mass near that of the target, which can be formed by nucleon transfer in a grazing reaction. No evidence is found for a general type of "buckshot" mechanism. Small yields of Na^{24} and P^{32} appear to result from a fission or fragmentation mechanism.

INTRODUCTION

SEVERAL mechanisms of heavy-ion reactions have been proposed in recent years. However the validity and relationship of these mechanisms in accounting for the major yields of heavy products (mass comparable to that of target) is not yet clear. At small and at large impact parameters, respectively, the situation is relatively straightforward. In a headon (or near headon) collision a compound nucleus of low angular momentum, de-exciting to the expected spallation products is presumably formed. In distant collisions, in which the Coulomb barrier is not penetrated, tunneling of a nucleon may occur,[1] generally leading to products one mass number removed from target and projectile, respectively.[2,3]

The role of collisions of intermediate impact parameters in contributing to the observed heavy products is less clear. One view is that any collision in which the Coulomb barrier is penetrated will lead to a compound nucleus containing all nucleons and likely to have high average angular momentum[4] (hereafter referred to as a "complete fusion compound nucleus" CFCN). Another view, generally referred to as the "buckshot" hypothesis,[5] holds that the projectile tends to break up in the field of the target and that, depending on the impact parameter, some fraction of its constituent nucleons is captured. A complete range of "partial fusion compound nuclei" (PFCN) ranging in mass from that of the target to that of the CFCN is thus to be expected. These compound nuclei will be excited to an extent corresponding largely to the kinetic energy of the captured nucleons, and will de-excite by the familiar evaporation process. Product distribution found in early work[5] originally suggested that such a range of compound nuclei were indeed formed. However, it was later pointed out that preferential alpha emission, which might be expected in complete fusion compound nuclei formed at high impact parameters and possessing many units of angular momentum, can also account for these product distributions.[6,7] Indications of such preferential alpha

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