appears to be too steep to be fit by the theory. A potential-scattering cross section larger than presently reported might improve this fit.

The derived width of the energy level for scattering was found to be 0.0052 ev, giving a ratio of Γ_n/Γ of 4.5 percent.

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The Decay of Rh^{104m} (4.3 Min) and Rh^{104} (44 Sec)

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The radiations of neutron-activated rhodium are studied with 180° constant field conversion electron spectrometers and a gamma-ray scintillation spectrometer. Internal conversion electrons are observed to be associated with the 4.3-minute activity. These are interpreted as arising from two isomeric transitions of 51.1±0.2 and 77.2±0.2 kev in rhodium. By coincidence studies these two transitions are shown to be in cascade. The character of the radiations, as determined from the K/L ratios and lifetime considerations, appears to be $M1$ and $E3$, respectively. Additional gamma-rays of energy 550±10 kev and ~1.2 Mev (weak) are observed with the scintillation spectrometer. The 550-kev transition is associated with both the 44-second and the 4.3-minute periods and is assumed to follow the beta-decay and hence be in Pd^{104}.

INTRODUCTION

As early as 1935, Fermi and associates had observed[1] in rhodium, exposed to slow neutrons, induced radioactivities whose half-lives were 50 seconds and 5 minutes. Subsequent investigators[2] showed that these activities were in rhodium-104 following neutron capture in rhodium-103, and they noted the existence of associated conversion electrons with, however, considerable disagreement as to their energies. From absorption measurements it was concluded that an isomeric transition of about 50 kev in the 4.3-minute activity led to the 44-second beta-emitting level. This in turn was believed to emit a beta-ray of maximum energy about 2.5 Mev followed by a gamma-transition of about 400 kev in the resulting palladium nucleus.

More recent measurements with a scintillation spectrometer have given the metastable transition[3] energy as 52 kev and the transitions[4] in palladium as 560 kev and 1.1 Mev. Other investigators[5] had found for the latter, gamma-rays energies of 41, 180, and 950 kev. One report[6] concluded that most of the electromagnetic radiation observed was due to bremsstrahlung.

TABLE I. Conversion lines associated with the 4.3-minute Rh^{104} decay.

Electron energy (kev)	Relative intensity	Interpretation	Energy sum (kev)	Transition energy (kev)	K/L
27.9	14±3	K(Rh)	51.1	51.1	≳5
47.8	<3	L_1(Rh)	51.2		
54.0	63±9	K(Rh)	77.2	77.2	~0.6
74.1	100±15	L_2(Rh)	77.2		
76.7	8±2	M(Rh)	77.2		

THE PHOTOGRAPHIC SPECTROMETRIC STUDY

In the present investigation the radiations from neutron-activated rhodium are studied with 180° constant-magnetic-field photographic spectrometers and with sodium iodide (thallium-activated) crystal scintillation gamma-spectrometers.

The spectrometers were located close to the Argonne heavy-water-moderated pile so that the irradiated specimens could be transferred quickly from the pile to the spectrometer. The specimens were inserted and removed from the strong neutron flux by means of a pneumatic tube. The photographic spectrometer sources were made of very narrow strips of cellulose tape coated with rhodium oxide and mounted on Lucite frames. The entire frame was irradiated, many successive exposures being required to obtain a satisfactory spectrogram. The injection of the samples into and removal from the cameras was expedited by the use of quick-operating vacuum locks previously described.[7]

The photographic records were made using no-screen emulsion, either on duplitized film or as a single coating on glass plates. The internal conversion electron

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spectrum was studied from 9 kev up to high energy values (approx 2.5 Mev), using three different fixed magnetic fields to cover the different energy ranges. Mean values of the dispersions expressed in kev per mm of plate distance for the three magnetic fields are 0.73, 5.0, and 10.5.

Neutron capture produces the 44-sec activity directly, as well as indirectly, by disintegration of the 4.3-minute active nuclei, since freshly irradiated samples always show an initial decay of the 44-sec half-life. Hence, it is quite easy to discriminate between radiations associated with each activity. Five low energy conversion electron lines are found to be associated with the 4.3-minute activity. Their energies, together with their interpretations and their intensities, are shown in Table I. An almost perfect fit results from the use of the work functions of rhodium, showing these gamma-transitions precede beta-emission. The two isomeric gamma-rays have energies of 51.1 and 77.2 kev. These energies are believed to be accurate to ± 0.3 percent.

Relative intensities of the conversion lines are determined from areas under line profiles obtained from photodensitometer traces of the plates. The measured values are corrected for attenuation due to the geometry of the spectrometers and for energy sensitivity of the emulsion. To correct for the geometrical attenuation, each area is multiplied by its corresponding radius of curvature. The energy sensitivity of the no-screen emulsion was determined by the method of Rutledge, Cork, and Burson.[7] The resulting relative intensities and K/L ratios are listed in Table I. No correction is made for differential absorption of the electrons in the source. This might be appreciable, particularly for the K electrons of the 51-kev gamma-ray, and if applied would result in a larger value for the K/L ratio.

From a comparison of the observed ratios with the empirical K/L *versus* Z^2/E relationships,[8] the 51-kev transition would appear to be $M1$ or $M2$. The 77-kev transition would be in best agreement with $E3$ with some possibility of being $E4$ or $M4$.

The lifetimes for an $M1$ and $M2$ transition of 51 kev are expected to be $\sim 10^{-9}$ and $\sim 10^{-2}$ sec, respectively. Lifetimes predicted for $E3$, $E4$, and $M4$ transitions of energy 77 kev are $\sim 10^{2}$, $\sim 10^{9}$, and $\sim 10^{11}$ sec. The experimental half-life (4.3 min) indicates again that the 77-kev transition is $E3$ and that it precedes the 51-kev. In view of the results of coincidence experiments described below, the short-lived $M1$ is a preferred assignment for the 51-kev transition. It may be further noted that the best fit is obtained by using the L_1 work function for the 51-kev transition. It has been demonstrated[9] that L conversion is largely in the L_1 subshell for $M1$ transitions.

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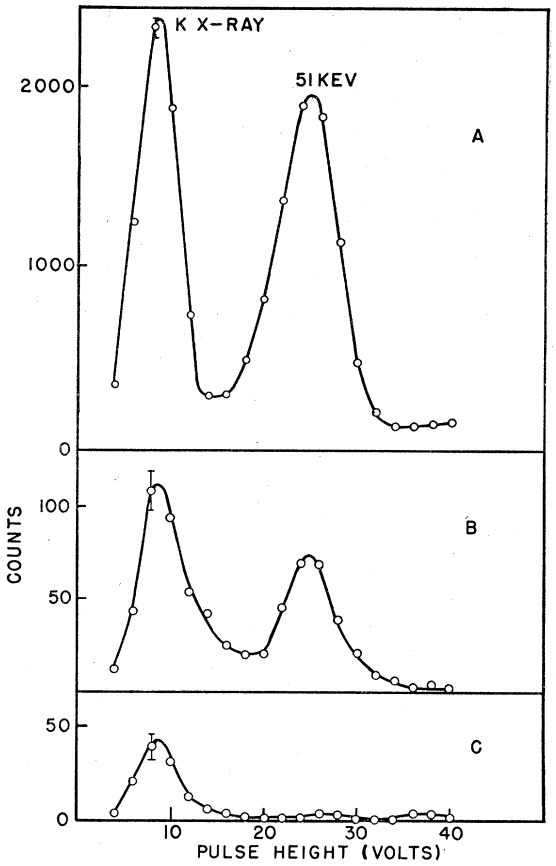

FIG. 1. Normal and coincidence pulse height distributions of rhodium (4.3-minute) in the region 10–80 kev: A. Normal distribution (background subtracted); B. Coincidence distribution with single channel set at the x-ray peak (accidental coincidences subtracted); C. Coincidence distribution with single channel set at the 51-kev peak (accidental coincidences subtracted). Intensities of peaks in B and C are not directly comparable.

SCINTILLATION SPECTROMETER STUDY

To evaluate the energies of gamma-rays which show little or no conversion, other methods must be employed. For this purpose the scintillation equipment used by Hamermesh and Hummel[10] in the study of capture gamma-rays was kindly made available. This consists of two spectrometers, one of which is provided with a twenty-channel pulse-height discriminator and the other with a single channel. These may be operated independently or in coincidence. The detecting probes are NaI(Tl) crystals packaged according to the method of Swank and Moenich[11] with No. 5819 photomultiplier tubes and associated preamplifiers. By a proper choice of gain and photomultiplier voltages, any region of the energy spectrum can be investigated. The coincidence resolving time is about 7 microseconds.

Sources consisted of small pieces of thin rhodium foil or small amounts of the oxide covered with cellulose

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[11] R. Swank and J. Moenich, Rev. Sci. Instr. **23**, 502 (1952).

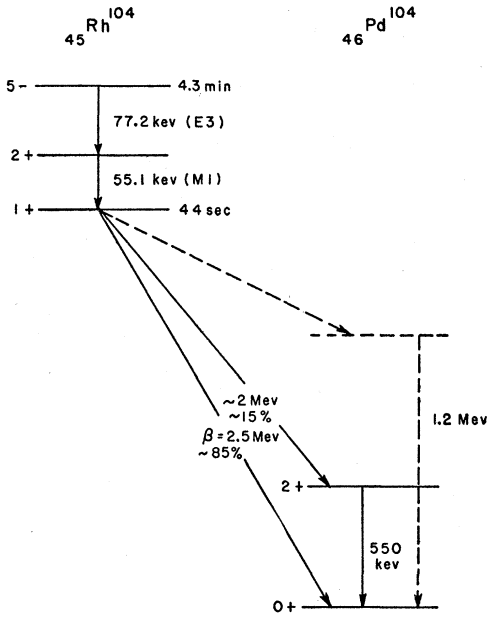

FIG. 2. Proposed decay scheme for Rh^{104} and Pd^{104}.

tape. A beryllium filter of about 1.8 grams per cm^2 was used to shield the crystal from beta-radiation. As a single spectrometer, peaks were observed in the pulse height distribution corresponding to energies of 20, 51, 550, and 1200 kev. These values are meaningful to about plus or minus two percent. The 20-kev peak is undoubtedly due to the rhodium K x-ray. This and the 51-kev peak decayed with the 4.3-minute half-life while the 550-kev peak decayed with both the 44-second and 4.3-minute periods. The 1200-kev peak is very small. Its decay was not measured. Conversion is apparently so complete for the 77-kev transition that it is scarcely apparent as a gamma-peak.

A search for gamma-gamma and gamma-x-ray coincidences was made by setting the single channel in succession at each of the prominent peaks and observing the resulting coincidence rates in the regions of the other peaks. The sources were first allowed to decay until the 44-second activity was in equilibrium with the 4.3-minute parent. During the coincidence counting the decay of the single channel counting rate was recorded.

The observed normal and coincidence spectra of Rh^{104} in the region 10–80 kev are displayed in Fig. 1. Figure 1(A) is the normal spectrum observed with the source in position for coincidence counting. Figure 1(B) is the coincidence spectrum observed with the single channel set at the x-ray peak. Figure 1(C) is the coincidence spectrum with the single channel set at the 51-kev peak. These data indicate that x-ray transitions are in coincidence with x-ray transitions and with 51-kev transitions. This is what is expected if the partially converted 51-kev and highly converted 77-kev transitions are in cascade. No x-ray or gamma-coincidences are observed involving the 550-kev transition. There is some evidence that the 550-kev gamma is in coincidence with the beta-transition, but the evidence is not certain. Counting rate limitations with the available apparatus prevented a decisive beta-gamma-coincidence experiment.

CONCLUSIONS

Since the 550-kev transition decays with the 44-second as well as the 4.3-minute periods, it must follow the beta-emission, and thus occur in Pd^{104}. The lack of strong coincidence with beta-radiation may indicate a branching in the beta-decay. This would be consistent with a report[12] by Sizoo and Friele, who estimated that there were only 15 electromagnetic quanta for every 100 electrons associated with the 44-second beta-radiation. The 550-kev gamma-ray is probably an $E2$ transition, since it is a transition from the first excited state to the ground state in an even-even nucleus.[13]

The 1.2-Mev transition is much less intense than the 550-kev gamma-ray. This peak may be due to an impurity. If it is indeed a transition in Pd^{104}, the existence of a third lower energy branch in the beta-decay is indicated. These data may be assembled and shown graphically in a reasonable nuclear level scheme as presented in Fig. 2. The ground state of the even-even Pd^{104} nucleus must be characterized by zero spin and even parity. The log ft for the 2.5-Mev beta-transition, assuming a 6 to 1 branching ratio, is only 4.7,[14] indicating a highly allowed transition, hence with spin change one and no parity change. This leads to a spin of one and even parity for the ground state of Rh^{104}. This is in agreement with the independent particle model with the odd proton and neutron in $g_{9/2}$ and $g_{7/2}$ orbits. Since no cross-over transition is observed, and in view of the observed character of the transitions, the excited states are assigned spins of two and five with even and odd parity, respectively. A simple configuration of $g_{9/2}$, $d_{5/2}$ is in agreement with experiment for the first excited state. However, a configuration involving more than a single odd neutron is required to explain the spin of five and odd parity which is assigned to the second excited state. A possibility is that the odd proton is $p_{\frac{1}{2}}$, while three or more $d_{5/2}$ or $g_{7/2}$ neutrons contribute the remaining 9/2 to the spin.

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