just been shown that the nuclear charge rotation is the principal contributor to the magnetic moment because of the electronic slippage. Calculation shows that the coefficient of the $K^2/J(J+1)$ term in the first summation in Eq. (9) is indeed very small, thus making the g-factor essentially independent of the quantum numbers. However, this situation should be regarded as somewhat accidental. In a more general case, a dependence of the g-factor on rotational quantum numbers is to be expected. The case of the water molecule, discussed in Sec. IV, indirectly supports this viewpoint.

The author is greatly indebted to Professor J. H. Van Vleck for advice concerning the theoretical aspects of this paper.

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Radioactivities of Ru^{105}, Rh^{105}, Br^{84}, and Br^{83}

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A lens spectrometer was used to study the disintegrations of Ru^{105} (4.5 hr), Rh^{105} (36.2 hr), Br^{84} (32 min), and Br^{83} (2.4 hr). Ru^{105} emits a simple beta-spectrum with an end-point energy of 1.150±0.006 Mev. This is followed by a 0.726-Mev gamma-ray to a metastable level in Rh^{105}. The decay to the ground state of Rh^{105} proceeds with a gamma-ray of about 0.1 Mev, with a half-life of 45 seconds. The ground state of Rh^{105} emits a simple beta-spectrum of 0.570±0.005 Mev. No gamma-ray appears to be associated with this decay. Br^{84} emits a complex beta-spectrum which can be resolved into at least four groups with end points and relative intensities of 4.679 Mev (40 percent), 3.56 Mev (9 percent), 2.53 Mev (16 percent), and 1.72 Mev (35 percent). The 4.679-Mev group, which goes directly to the ground state of Kr^{84}, does not have a forbidden spectrum shape. It is suggested that the 32-minute half-life may be associated with an isomeric level above the ground state of Br^{84}. The decay of Br^{83} consists of a single beta-ray group with a maximum energy of 0.940±0.010 Mev.

I. INTRODUCTION

The availability of a large magnetic lens spectrometer, located close to a nuclear reactor, suggested the possibility of a more detailed investigation of the disintegration of Ru^{105} (4.5 hr), Rh^{105} (36.2 hr), Br^{84} (32 min), and Br^{83} (2.4 hr). The spectrometer measurements have been supplemented by coincidence and absorption studies.

Ru^{105} decays by negatron emission to Rh^{105}, which in turn goes to Pd^{105}. Earlier investigations,[1–3] using absorption techniques, report values for the beta-ray end point of 1.3, 1.4, and 1.5 Mev, and values for the energy of a gamma-ray of 0.7 and 0.76 Mev. The Rh^{105} activity was reported[1,2,4,5] again by absorption methods, to have a beta-ray of end-point energy between 0.5 and 0.78 Mev. A weak gamma-ray of 0.3 Mev has also been reported.[1,5]

In addition to yielding more precise values of the beta- and gamma-ray energies, the present investigation has revealed the existence of a 45-second metastable level located about 0.1 Mev above the ground state of Rh^{105}. The 0.3-Mev gamma-ray previously associated with the Rh^{105} activity was not observed. An energy level scheme for the Ru^{105}–Rh^{105}–Pd^{105} transitions is suggested, which is not inconsistent with the predictions of the nuclear shell model.[6,7]

The investigation of the Br^{84} activity was instituted mainly because earlier considerations, based on the available data and on the predictions of the nuclear shell model,[6,8] suggested that the high energy beta-transition should, if it were between the ground states of Br^{84} and Kr^{84}, exhibit a spectrum shape characteristic of a forbidden transition. Earlier absorption work[9,10] reports values of 5.3 and 4.5 Mev for the maximum energy of the beta-rays. The results of the present investigation show that the Br^{84} beta-decay is complex, consisting of at least four groups. Moreover, the highest energy group, with end-point energy of 4.679±0.010 Mev is found to have an allowed shape. Since coincidence experiments indicate that this transition is directly to the ground state of Kr^{84}, the absence of a forbidden shape is inconsistent with what appear to be very reasonable predictions of the nuclear shell model.

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[‡] This work was performed under the auspices of the AEC.

[1] Sullivan, Sleight, and Gladrow, Plutonium Project Report CC-1493 (1944), unpublished.

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

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[10] H. J. Born and W. Seelmann-Eggebert, Naturwiss. **31**, 201 (1943).

It is suggested that the 32-min half-life may be characteristic of a metastable level feeding the ground state of Br^{84}. Under such conditions, the beta-transition to the ground state of Kr^{84} would be allowed and the half-life would be expected to be less than 5 sec. Such an allowed transition is provided by one interpretation of the shell model.[6,7] An attempt to isolate the lower isomeric state by means of a Szilard-Chalmers separation was unsuccessful.

The measurement of the Br^{83} spectrum was obtained as a by-product of the Br^{84} investigation. End-point values of 1.05 and 0.9 Mev had been obtained earlier by absorption.[11,12] No gamma-radiation was found.[13,14] From the present study, it appears that the beta-spectrum is simple, with an end point of 0.940±0.010 Mev.

II. EXPERIMENTAL PROCEDURE

The energy measurements were made in the large magnetic lens spectrometer described in another paper.[15] A G-M tube with a 3.6-mg/cm^2 mica end window and a 0.5-inch diameter aperture was employed as a detector. With sources of 0.5-inch diameter, the instrument was operated at resolutions of both 3 and 6 percent. The decay periods of all spectra and lines were checked in the spectrometer.

The beta-gamma- and gamma-gamma-coincidence measurements were made with an arrangement employing two anthracene scintillation counters and an amplifier with a resolving time of 0.2μsec.

The Ru^{105} was made by a (n,γ) reaction on Ru^{104}. Normal ruthenium, previously purified by distillation from perchloric acid was activated by neutron irradiation in the thermal column of a nuclear reactor. Short irradiation times produced a negligible intensity of the 41-day Ru^{103}. The source used for the measurement of the beta-spectrum consisted of powdered ruthenium metal, uniformly deposited on a thin aluminum backing. The thickness of the ruthenium was 12 mg/cm^2 and of the backing, 1.4 mg/cm^2. The half-life of 4.5 hours was checked at various points of the spectrum, and also in the coincidence experiments.

The Rh^{105} was prepared by beta-decay of Ru^{105} Purified ruthenium trichloride was irradiated with slow neutrons. The 4.5-hr Ru^{105} was allowed to decay and the ruthenium then was distilled away from the Rh^{105} out of perchloric acid solution. The source used for the measurement of the beta-spectrum consisted of rhodium sulfide with a thickness of 0.7 mg/cm^2 mounted on aluminum foil of thickness 1.4 mg/cm^2. The thickness of the deposit was quite uniform. The source decayed with a half-life of 36.2 hours measured over six half-lives.

A 45-second isomeric state of Rh^{105}, found by the decay of the 4.5-hr Ru^{105}, was found by performing a rapid chemical separation of rhodium from ruthenium. Ruthenium trichloride, previously neutron-irradiated to produce Ru^{105}, was oxidized by perchloric acid to volatile RuO_4. The latter was then distilled from the solution and collected on a platinum plate cooled with dry ice. This was allowed to stand for a few minutes; and then the RuO_4 was vaporized by rapid heating, leaving the rhodium decay product on the platinum plate, on which it was counted directly.

Br^{83} and Br^{84} were separated from other uranium fission products. Uranyl nitrate, enriched in U^{235}, was irradiated in the thermal column of a nuclear reactor, then dissolved in nitric acid with the addition of bromine and iodine carriers. The bromine and iodine fission products were then distilled into 0.1N nitric acid containing sodium nitrite to reduce the bromine to bromide. The iodine was extracted into carbon tetrachloride and discarded. The bromide was then precipitated as silver bromide. Two sources were prepared for the determination of the Br^{84} beta-spectrum; the first had a thickness of 4 mg/cm^2 and the second a thickness of 2.5 mg/cm^2. Each was deposited on 7 mg/cm^2 of filter paper and mounted on 1 mg/cm^2 of aluminum. Only the second source was used in determining the Br^{83} spectrum after all Br^{84} had disappeared. The Br^{84} spectrum was found to decay with a half-life of 32 minutes over seven half-lives. The Br^{83} spectrum decayed with a half-life of 2.4 hours.

III. RESULTS

Ru^{105}

Figure 1 is a Fermi plot of the data obtained on the beta-spectrum of Ru^{105}. The resolution of the spectrometer was 6 percent. There is evidently only one group of electrons, and the spectrum is of the allowed form. The end point is 1.150±0.006 Mev. There was no

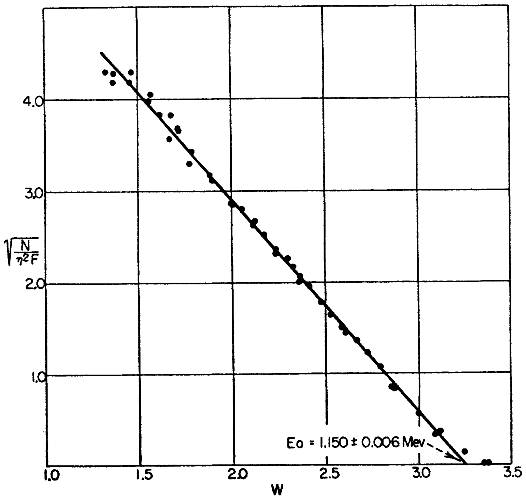

FIG. 1. Fermi plot of the Ru^{105} beta-spectrum.

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[11] A. Langsdorf, Jr., and E. Segrè, Phys. Rev. **57**, 105 (1940).

[12] L. E. Glendenin, NNES-PPR, Vol. 9B, No. 7.3.1 (1940), unpublished.

[13] A. H. Snell, Phys. Rev. **52**, 1007 (1937).

[14] L. E. Glendenin, Plutonium Project Report CC-920, 35 (1943), unpublished.

[15] L. M. Langer, Phys. Rev. **77**, 50 (1950).

evidence of any conversion electron lines at energies above 0.250 Mev.

A search was made for gamma-radiation, using both a 0.0006-in. uranium radiator and a 0.002-in. silver radiator and a strong source of Ru^{105} in the spectrometer. Compton and photo-electrons were found corresponding to a gamma-ray of 0.726±0.007 Mev. No other gamma-rays of energy greater than 0.125 Mev could be found.

Beta-gamma-, but no gamma-gamma-coincidences were found. Figure 2 shows an absorption curve on these coincidences. The beta-gamma coincidence rate per beta-particle is independent of absorber thickness, indicating that the 0.726-Mev gamma-ray is in cascade with the beta-ray.

From the absence of any measurable internal conversion, it is inferred that the 0.726-Mev gamma-radiation is of low polarity.

Rh^{105}

Figure 3 is a Fermi plot of the beta-spectrum of the 36.2-hr Rh^{105} taken with a resolution of 6 percent. The spectrum has an allowed shape and the decay evidently consists of only one group. The end point is 0.570±0.005 Mev. A careful search was made for internal conversion electrons in the neighborhood of 0.3 Mev. None were found.

A search was also made for gamma-radiation using a strong source and an anthracene scintillation counter detector. No measurable effect above background could be found.

45-Sec Rh^{105} Isomer

Considerations of the nuclear shell model for the Rh^{105} nucleus suggested the possibility that a short-lived isomer might exist but might have previously escaped detection. Rh^{103}, a similar nucleus, is known to have a 57-min metastable state. A rapid chemical separation of rhodium from Ru^{105} was made by the procedure described above. Figure 4 shows that the rhodium, so isolated, decays with a 45-sec half-life. A crude absorption curve on this activity yielded a range of 15 mg/cm^2 of Al, corresponding to an energy of approximately 0.1 Mev for the internal conversion electrons from the isomeric transition.§

Br^{84}

Figure 5 shows the momentum distribution of the beta-particles emitted by Br^{84}. The spectrum, taken with a resolution of 3 percent, is obviously complex. The broken curves show the results of an analysis into four groups on the basis of the Fermi plot illustrated in Fig. 6. The end points and relative contributions are: 4.679±0.010 Mev, 40 percent; 3.56 Mev, 9 percent; 2.53 Mev, 16 percent; 1.72 Mev, 35 percent. Because of the errors involved in performing the multiple subtractions in this analysis, it is difficult to estimate the accuracy of the end points and of the percentages to be attributed to the inner groups. On the assumption that the 32-min half-life is that of the ground state of Br^{84}, the log(ft) values to be associated with each group are respectively: 7.75, 7.9, 6.95, 5.9.

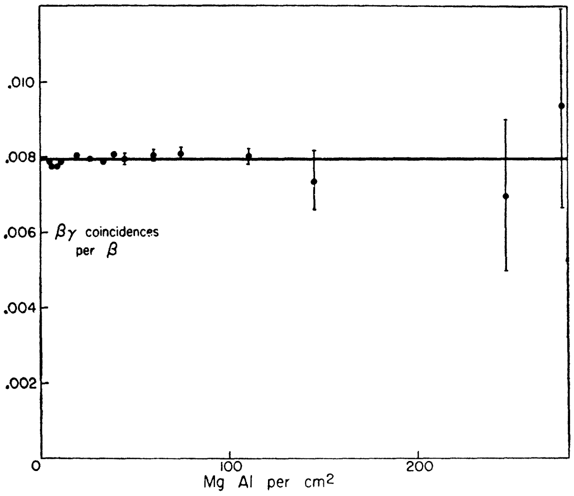

FIG. 2. Beta-gamma coincidence absorption of the Ru^{105} activity.

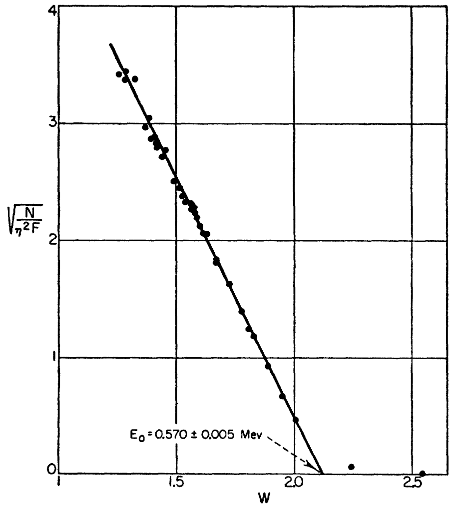

FIG. 3. Fermi plot of the Rh^{105} beta-spectrum.

It is significant that the highest energy group (4.679 Mev) yields a straight-line Fermi plot corresponding to an allowed spectrum shape. Under essentially identical conditions, the spectrum of Rb^{88}, which has an atomic number and maximum energy not very different from those of Br^{84}, was found to have a shape characteristic of a once-forbidden transition involving a change of two units of angular momentum and a parity change.[16]

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§ *Note added in proof:* Recently, P. Axel and R. B. Duffield have observed the K and L internal conversion lines in a magnetic spectrometer. From these measurements, the energy of the gamma-transition is 0.130±0.002 Mev. The ratio of K to L conversion is 1.4.

[16] Bunker, Langer and Moffat, Phys. Rev. **81**, 30 (1951).

The shape of the 4.7-Mev Br^{84} spectrum suggests then that the transition is either allowed or once-forbidden with a spin change of zero or one.

Results of coincidence measurements indicate that there are no gamma-rays associated with electrons of energy greater than 3.5 Mev. The 4.7-Mev group therefore appears to go directly to the ground state of Kr^{84}. Relatively large numbers of gamma-gamma-coincidences were observed, consistent with the complexity of the beta-ray spectrum.

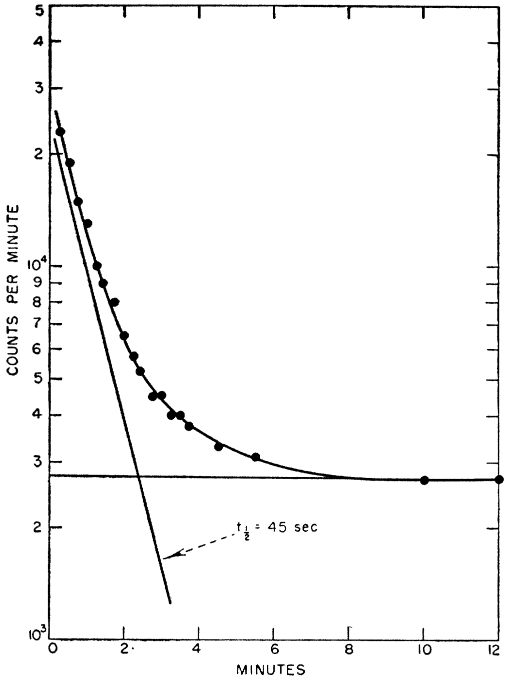

FIG. 4. Decay of the 45-sec Rh^{105} metastable state.

Because a sufficiently strong source was not readily available, no attempt was made to determine the energy of the gamma-rays in the spectrometer.

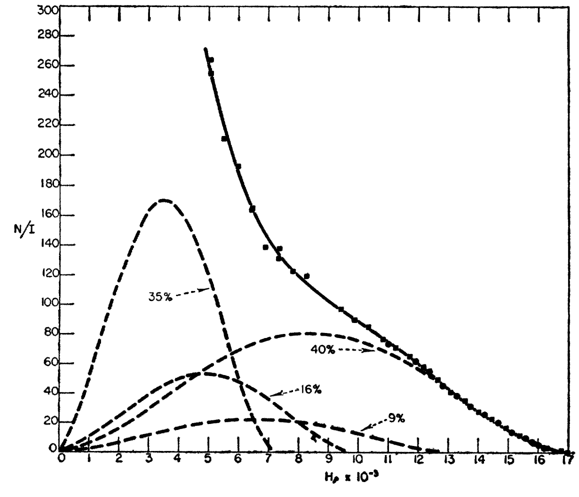

FIG. 5. Momentum distribution of the Br^{84} beta-rays. The broken line curves show the resolution into groups according to the Fermi plot analysis.

An unsuccessful attempt was made to separate the possible isomeric states of Br^{84} by chemical means. The Br^{84}, in the form of BrO_3^- in aqueous solution, was allowed to stand for a few minutes in contact with inactive Br_2. The Br_2 was then extracted into carbon tetrachloride, transferred to a counting cell placed around a Geiger tube, and the activity determined by automatic recording of the output of a scale of 256 unit. Any decay with a half-life between 30 sec and 10 min would have been observed. None was seen. It is concluded that the isomer, if it exists, has a half-life of less than 30 sec, or that the gamma-ray associated with the isomeric transition is not sufficiently converted to give a measurable chemical separation of the isomers.

Br^{83}

Figure 7 shows the momentum distribution of the electrons from Br^{83} taken with a resolution of 3 percent. These data were obtained with the same source as was used for the Br^{84} spectrum determination but after all the Br^{84} had decayed to a completely negligible intensity. Figure 8 is a Fermi plot of the beta-spectrum of Br^{83}. There appears to be only one group with an end point at 0.905±0.010 Mev.

IV. DISCUSSION AND CONCLUSIONS

Figure 9 shows a decay scheme for the $Ru^{105}-Rh^{105}-Pd^{105}$ transitions which accounts for the observed data and which is essentially consistent with present ideas on nuclear shell structure.[6–8]. The isomerism of Rh^{105} is understandable, since the $p_{1/2}$ and $g_{9/2}$ states appear to have closely the same energy.[6] The assignment of $g_{7/2}$ or $d_{5/2}$ to the high excited state in Rh^{105} is a guess based upon the assumption that all other states are already filled in the lower shell.

With the assignment of states as indicated in Fig. 9, the observed beta- and gamma-transitions would outcompete all other possibilities, as is required. The only weak point in the scheme appears to be the apparently

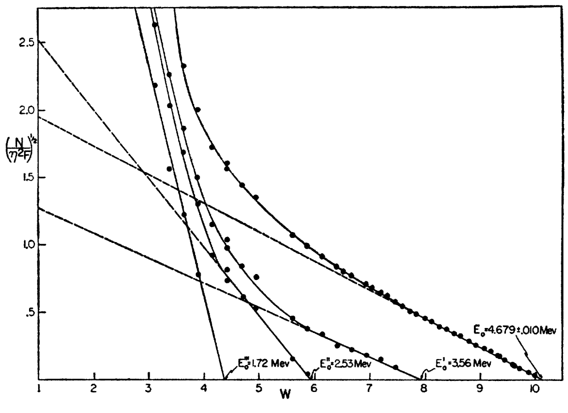

FIG. 6. Fermi plot of the Br^{84} beta-spectrum.

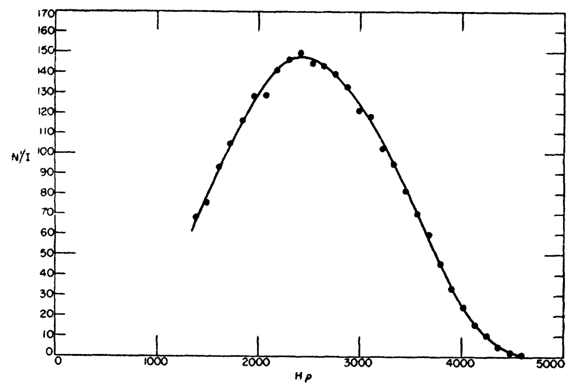

FIG. 7. Momentum distribution of the Br^{83} beta-rays.

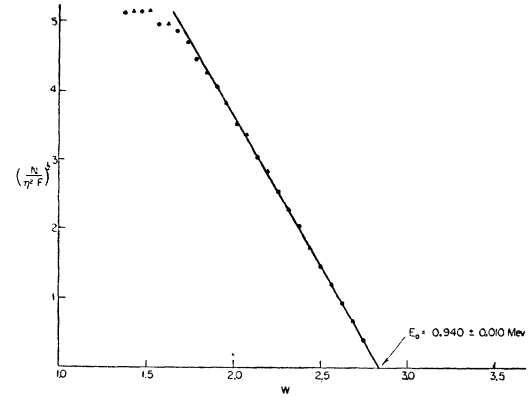

FIG. 8. Fermi plot of the Br^{83} beta-spectrum.

low comparative half-life ($\log ft = 5.5$) to be associated with the once-forbidden $p_{1/2}-s_{1/2}$ transition from Rh^{105} to Pd^{105}. An alternative assignment, which would obviate this difficulty, would be to invert the $g_{9/2}$ and $p_{1/2}$ levels in Rh^{105} and assign $g_{7/2}$ to the ground state of Pd^{105}. This, however, would require a $d_{3/2}$ level for the high excited state of Rh^{105}. Although the $d_{3/2}$ level is rather high up in the next shell, such an assignment for a high excited state is perhaps not unreasonable, so that this scheme may be preferable to that shown in Fig. 9. A measurement of the spin of Pd^{105} would be very informative.

The Br^{84} nucleus contains both an odd proton and an odd neutron. According to the concepts of the nuclear shell model, one might expect the thirty-fifth proton to be $p_{3/2}$ or possibly $f_{5/2}$. The forty-ninth neutron occurs in a region where $p_{1/2}$ and $g_{9/2}$ have about the same energy. If one attempts to form the resultant state for Br^{84} according to the empirical rules of Nordheim,[7] one gets the following possible combinations for the spin and parity:

$f_{5/2}+g_{9/2}$	2, odd
$f_{5/2}+p_{1/2}$	2, even
$p_{3/2}+g_{9/2}$	high, odd
$p_{3/2}+p_{1/2}$	1, even.

The ground state of Kr^{84}, which is an even-even nucleus, is presumably zero, even. One might expect, then, that for any of the first three combinations, the beta-transition from the ground state of Br^{84} to that of Kr^{84} should result in a spectrum with a shape measurably different from that found for allowed transitions.[17] Only the $p_{3/2}-p_{1/2}$ combination would provide for the observed allowed spectrum shape of the 4.679-Mev transition which, according to the coincidence measurements, does go to the ground state of Kr^{84}. However, the high comparative half-life (based upon a 32-min decay) would be inconsistent with the allowed character of such a transition. It is therefore suggested that the 32-min half-life might be associated with an isomeric level somewhat above the $p_{3/2}-p_{1/2}$ ground state of Br^{84}. Excitation of the odd proton to form the $p_{3/2}-g_{9/2}$ combination would provide the conditions necessary for isomerism. The known isomerism in the neighbor odd-odd nucleus Br^{80} offers some precedent for this idea. Under such circumstances, one would expect the half-life of the ground state of Br^{84} to be less than 5 seconds.

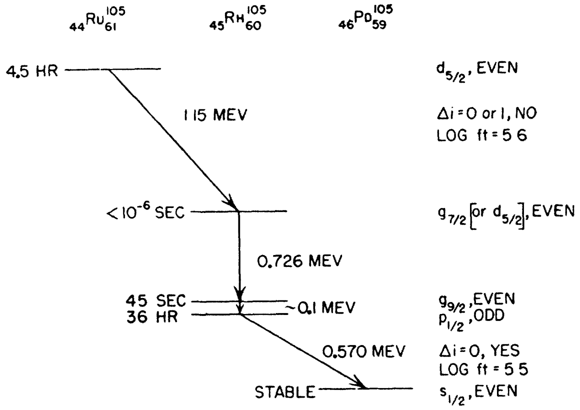

FIG. 9. Energy level diagram for the $Ru^{105}-Rh^{105}-Pd^{105}$ decay.

The 2.4-hr Br^{83} decay appears to be simply that of an allowed transition from the $p_{3/2}$ ground state of Br^{83} to the $p_{1/2}$ ground state of Kr^{83}. On the basis of the 0.94-Mev end point and the 2.4-hr half-life, the $\log(ft)$ for this transition is 5.0.

The authors would like to acknowledge the cooperation of many members of the Los Alamos Scientific Laboratory. In particular, they want to thank Mr. A. Freedman and Mr. R. D. Moffat for help in making some of the measurements.

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[17] L. M. Langer and H. C. Price, Jr., Phys. Rev. 76, 644 (1949).