Low-Energy Nuclear Level Scheme of Rh^{104}

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Investigations of the low-energy level properties (level energies, spins, and parities) of Rh^{104} have been undertaken from studies of the coincidence relationships existing between the low-energy capture gamma rays produced by thermal neutron capture in Rh^{103} using NaI(Tl) scintillation crystals as detectors. It is known from the decay scheme of the 4.4-min Rh^{104m} isomer that Rh^{104} has energy levels at 52, 96, and 129 keV with spins and parities of 2−, 2+, and 5+, respectively. The data obtained in these investigations have been combined with the isomeric level data in order to determine the properties of several additional levels. Additional levels in Rh^{104} have been determined at the following energies, with the level spin and parity in parenthesis after the energy; 184 keV (1±), 192 keV (3+), 269 keV (3±), 450 keV, and either 229 keV (3+) or 325 keV (4+). These spin and parity assignments were made on the basis of a K internal conversion coefficient analysis of the coincidence data together with consideration of the relative cascade intensities. On the basis of the possible odd-proton and odd-neutron configurations open to the 184- and 269-keV levels, and considering the transition intensities to the lower levels, it was determined that the negative-parity assignment is most probable for both of these levels, with the levels having configuration assignments of $(p_{3/2})(d_{5/2})$. The 192-keV level together with the 229- or 325-keV level most probably have either $[(g_{9/2})^5]_{7/2}(d_{5/2})^n$ or $(g_{9/2})^5(d_{5/2})^n$ configurations. In fact, if it is the 229-keV level which does exist, as the available evidence might seem to indicate, then, since they both have spins and parities of 3+, the 192-keV level would have one of these configurations while the 229-keV level would have the other.

INTRODUCTION

INVESTIGATIONS of the low-energy level properties of Rh^{104} have been accomplished both from studies of the 4.4-min isomeric gamma decay of the 129-keV Rh^{104m} level and from investigations of the neutron capture gamma rays produced by thermal neutron capture in stable Rh^{103}. In the recent investigations of the isomeric gamma decay of Rh^{104m} by Greenwood[1] it was determined that decay from the 129-keV isomeric level occurred to the ground state through two intermediate levels at 96 and 52 keV. This Rh^{104m} gamma-decay scheme is shown in Fig. 1.

Investigations of rhodium neutron capture gamma rays have been reported by several authors[2–5] using a variety of detection techniques. Bartholomew and Kinsey[2] used a magnetic pair spectrometer to obtain the capture gamma-ray spectrum at energies above approximately 3 MeV. The highest energy line they observed was at 6.792 MeV and this was tentatively assigned as the ground-state transition, although there was some evidence for a transition having a higher energy at around 7.0 MeV. On the basis of a 6.792-MeV ground-state transition, it was suggested that the observed lower energy gamma rays occurred in transitions to energy levels at 440, 590, 730, 880, and 1240 keV. The high energy rhodium capture gamma-ray spectrum observed by Groshev *et al.*[3] using a magnetic Compton spectrometer was identical to that found by Bartholomew and Kinsey.[2]

Estulin *et al.*[4] studied the low-energy (less than 300 keV) capture gamma-ray spectrum of Rh^{104} using a single-crystal NaI(Tl) scintillation spectrometer. In column 3 of Table I. the low-energy lines observed in that work are shown, together with their observed intensities (in units of the number of gamma rays of that particular energy produced in 100 neutron captures) in column 4. It was suggested that, by assuming

TABLE I. Low-energy thermal neutron capture gamma rays of rhodium observed in these experiments together with those lines previously reported. Intensities are in units of the number of capture gamma rays produced in 100 thermal neutron captures.

Present work Energies (keV)	Intensity	Estulin *et al.*[a] Energies (keV)	Intensity	Draper[b] Energies (keV)	Intensity
20.1 (Rh K x ray)	26				
51.5	11			50	17
97.2	18	96	17	94	24
133.2	9.5	133	$\leqslant 8$	131	6
181	25	176	19	185	23
217	14	217	9	220	10
269	7				
327	7				
432 (possibly multiple)					
644	3.3				

[a] See reference 4.
[b] See reference 5.

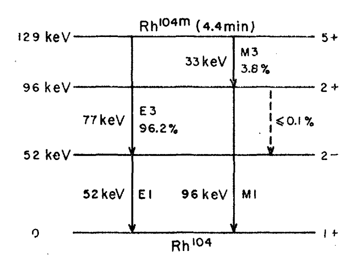

FIG. 1. The gamma-decay scheme of the 4.4-min isomer of Rh^{104} proposed by Greenwood (see reference 1).

[1] R. C. Greenwood, preceding paper [Phys. Rev. **129**, 339 (1963)].
[2] G. A. Bartholomew and B. B. Kinsey, Can. J. Phys. **31**, 1025 (1953).
[3] L. V. Groshev, A. M. Demidov, V. N. Lutsenko, and V. I. Pelekhov, *Atlas of γ-Ray Spectra from Radiative Capture of Thermal Neutrons* (Pergamon Press, New York, 1959).
[4] I. V. Estulin, L. F. Kalinkin, and A. S. Melioranskii, Nucl. Phys. 4, 91 (1957) and J. Exptl. Theoret. Phys. (U.S.S.R.) **31**, 886 (1956).
[5] J. E. Draper, Phys. Rev. **114**, 286 (1959).

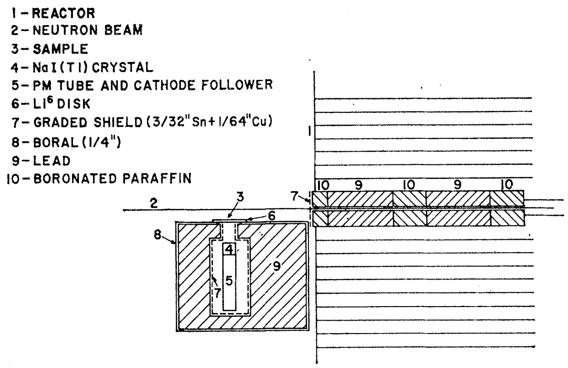

FIG. 2. The neutron collimator and the detector shielding arrangement.

a level at 230 keV these transitions could be fitted into a level scheme consistent with the level scheme suggested by Bartholomew and Kinsey[2] together with the 52- and 128-keV levels observed by Jordan *et al.*[6] in the isomeric decay scheme of Rh^{104m}. However, it was pointed out that in their proposed level decay scheme, it is difficult to reconcile the equality of a 96-keV transition between the 230-keV level and the isomeric level at 128 keV to that of the 176-keV transition between the 230- and the 51-keV levels. This is especially anomalous when it is remembered that the neutron capture cross section for production of Rh^{104} by the $Rh^{103}(n,\gamma)Rh^{104}$ reaction is 138 b and only 12 b for the production of the Rh^{104m} isomer, while the 96-keV transition was measured as occurring in 17% of all neutron captures.

The low-energy neutron capture gamma-ray spectrum of rhodium has also been observed by Draper[5] using a 2.5-in.×1.7-in. NaI(Tl) crystal as a detector. The capture gamma-ray spectrum was similar to that seen by Estulin *et al.*[4] with the exception that a 51-keV line was visible in the spectrum obtained by Draper.[5] The energies and intensities of these lines are shown in columns 5 and 6 of Table I.

More recently, da Silva and Buechner[7] investigated the Rh^{104} energy levels by analyzing the reaction protons from the (d,p) reaction of 7.0-MeV deuterons on rhodium using a high-resolution magnetic spectrograph. Proton groups corresponding to 33 levels below a 1.5-MeV excitation energy in Rh^{104} were observed. The lowest energy levels were observed to have energies at 221, 344, 379, 414, 442, 473 keV, etc., and possibly at 137 keV. However, since such a level scheme does not agree with the level scheme of the 4.4-min isomer of Rh^{104}, it was suggested that there was some possibility that the highest energy proton group corresponds to the excited state at 51 keV. It was pointed out that this is plausible since the target nucleus has its odd protons in a $(p_{1/2})$ configuration and the 51-keV level in Rh^{104} also has such a $(p_{1/2})$ proton configuration, while the Rh^{104} ground state has a $(g_{9/2})_{7/2}$ proton configuration and the 129-keV level has either a $(g_{9/2})_{7/2}$ or a $(g_{9/2})$ configuration. It was noted by da Silva and Buechner[7] that the measured Q value in their work was approximately 200 keV greater than the Q value predicted on the basis of neutron capture gamma-ray spectra.[2,3] The possible 7.0-MeV transition reported by Bartholomew and Kinsey[3] could remove this discrepancy, although the tentative energy levels reported by them would then be approximately 200 keV too low and there would be an additional level at about 200 keV.

In this study, the low lying energy level properties of Rh^{104} have been investigated using the neutron capture gamma rays produced by thermal neutron capture in Rh^{103}. This work was undertaken to try to remove some of these inconsistencies found in the low-energy Rh^{104} level scheme.

EXPERIMENTAL

A. Neutron Capture Gamma-Ray Scintillation Spectra

The Armour Research Reactor was used as the source of neutrons for these experiments. For a maximum reduction in background it is desirable to minimize the fluxes of fast neutrons (here defined as those neutrons with energies above the cadmium cutoff) and reactor gamma rays relative to the thermal neutron flux, while still keeping a workable thermal neutron flux. Consequently, a reactor port which runs tangential to the reactor core, and 13 in. from it at the distance of closest approach, was selected for these experiments. To minimize the fast neutron flux, graphite plugs were inserted into the region of the port closest to the reactor core so that neutrons were required to travel through at least 20 in. of graphite before leaving the central region of the reactor through this port.

Rhodium capture gamma-ray spectra were obtained using both $1\frac{1}{2}$-in.×1-in. and 3-in.×3-in. NaI(Tl) scintillation detectors. One of the $1\frac{1}{2}$-in.×1-in. NaI(Tl) crystals used had a 0.001-in.-thick aluminum gamma-ray entrance window to facilitate more accurate intensity measurements on the low-energy capture gamma-ray lines. Pulse-height analysis was accomplished using a 512-channel pulse-height analyzer. The NaI(Tl) scintillation detector, together with its associated shielding and the neutron collimator (in place in the reactor port), is shown in Fig. 2. This neutron collimator consisted of alternate layers of lead and boronated paraffin with a $\frac{5}{8}$-in.-diam hole for the neutron beam to pass through. The detector shielding consisted of lead (having a minimum thickness of 2 in.) which in turn was shielded by $\frac{1}{4}$-in. boral sheet (containing 35% boron carbide). In this way, scattered neutrons were prevented from being captured in the lead with the emission of the 7.38-MeV capture gamma rays. Instead, such scattered neutrons were captured by the boron with the resultant

[6] W. C. Jordan, J. M. Cork, and S. B. Burson, Phys. Rev. **90**, 862 (1953).
[7] A. G. da Silva and W. W. Buechner, Bull. Am. Phys. Soc. **7**, 83 (1962), and Massachusetts Institute of Technology Laboratory for Nuclear Science Progress Report, 1961 (unpublished).

478-keV gamma rays, produced in the $B^{10}(n,\alpha)Li^7$ reaction, being captured in the lead. The sample is viewed by the NaI(Tl) crystal through a collimator hole in this lead shield. Since the rhodium sample will have an appreciable cross section for neutron scattering, it is essential that this collimator hole be covered over with a neutron absorber. Boron is not suitable for this task since it produces 478-keV gamma radiation in the $B^{10}(n,\alpha)Li^7$ reaction. Lithium however, is ideal for the neutron shield since the predominant $Li^6(n,\alpha)H^3$ reaction produces no gamma rays. However, a neutron shield made of natural lithium fluoride (fluorine has a 9-mb thermal neutron capture cross section) would be sufficiently thick to cause appreciable gamma-ray attenuation in the low-energy regions. Consequently, a quantity of Li^6F (lithium fluoride enriched to 95.6% in Li^6) was obtained from the Stable Isotopes Division of Oak Ridge National Laboratory for this neutron screen.

A typical rhodium low-energy capture gamma-ray spectrum obtained using a $1\frac{1}{2}$-in.$\times$1-in. NaI(Tl) crystal (not the thin window crystal assembly), is shown in Fig. 3. To obtain this spectrum, a 36-mg sample of spectroscopically pure rhodium sponge was compacted into a uniformly thick $\frac{5}{8}$-in.-diam disk contained in pure aluminum foil (the total mass of the aluminum was 38 mg). To reduce the background effects, this disk sample was suspended on a set of fine tungsten cross wires in the neutron beam. Even with this arrangement though, there was still a reasonably large background. This background was produced in a variety of ways, e.g., by capture gamma-ray production in the shielding and surroundings, fast neutron scattering off the sample and surroundings into the NaI(Tl) crystal, gamma rays produced in the inelastic scattering of fast neutrons (energies in the keV and MeV region) in the source and surroundings, reactor gamma rays scattered into the crystal by the sample and the surroundings, etc. These background effects can be corrected for by taking the following four spectra:

(1) Rhodium sample in the neutron beam.

(2) Rhodium sample in the beam, with the thermal neutrons removed from the beam by a cadmium shutter located in front of the neutron collimator.

(3) The rhodium sample removed from the beam (but with the sample holder and an equivalent empty aluminum sample container still in the beam) with the cadmium shutter still in the neutron beam.

(4) No sample or cadmium shutter in the beam.

Rhodium capture gamma-ray spectra produced by thermal neutron capture, such as is shown in Fig. 3, were therefore obtained from the following combination of the above spectra:

$$1-2+3-4. \tag{1}$$

This procedure was first suggested by Hamermesh and Hummel.[8] The arithmetic required in (1) was accomplished internally in the 512-channel analyzer by storing data in two sets of 256 channels.

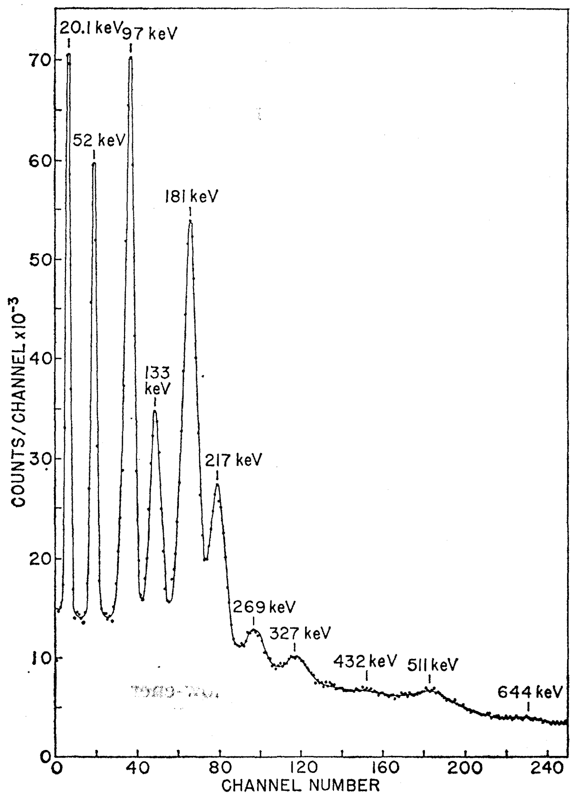

FIG. 3. The low-energy neutron capture gamma-ray spectrum of rhodium obtained with a $1\frac{1}{2}$-in.$\times$1-in. NaI(Tl) scintillation detector.

From the rhodium capture spectrum shown in Fig. 3 it can be seen that, in addition to the low-energy lines observed by Estulin *et al.*[4] and Draper,[5] lines are visible at 269 and 327 keV together with the rhodium K x-ray peak. Also from the capture spectra obtained with the 3 in.$\times$3 in. NaI(Tl) crystal it became apparent that there were also very weak lines at 432 keV (possibly a multiple peak) and 644 keV. The peak at 511 keV is most probably accountable for as due to the annihilation radiation. The energies of these Rh^{104} capture lines together with their measured intensities (in units of the number of capture gamma rays produced in 100 neutron captures) are given in columns 1 and 2 of the Table I. To determine the absolute intensities of these capture gamma rays it was necessary to compare these line intensities to the intensity of the 478-keV line produced in thermal-neutron capture by a boron sample having an accurately known area. This was accomplished by using an accurately machined $\frac{5}{8}$-in. disk to contain the boron sample which was thick enough to capture more than 99% of the thermal neutrons entering it. To obtain suitable spectra with the boron sample the same subtraction process as described by Eq. (1) was used. In this boron spectrum, the 478-keV gamma rays are produced

[8] B. Hamermesh and V. Hummel, Phys. Rev. 88, 916 (1952).

in 89.7% of all the resulting $B^{10}(n,\alpha)Li^7$ reactions.[9] Thus, by using the published values of the rhodium capture cross section together with the measured rhodium sample mass, and after making appropriate corrections to the rhodium and boron peak intensities for detection efficiencies, photopeak efficiencies, attenuations through the intervening materials, and self-absorption in the rhodium, the capture gamma-ray intensities could be determined. In the determination of these intensities, the principal error (especially in the weaker peaks) occurs in the estimation of the background level from the Compton continuum due to the higher energy gamma rays. To determine the magnitude of this Compton continuum in the region below approximately 100 keV, additional measurements of the rhodium capture gamma-ray spectra were made with a $\frac{3}{32}$-in. tin plus $\frac{1}{64}$-in. copper attenuator located between the sample and the NaI(Tl) crystal to remove these low-energy peaks from this region of the spectra and leave only the Compton background (slightly attenuated).

B. Coincidence Experiments

Coincidence studies of the low-energy rhodium capture gamma rays were accomplished using two $1\frac{1}{2}$-in.×1-in. NaI(Tl) crystals as detectors. Both scintillation detectors were mounted in detector shields identical to the one shown in Fig. 2, with the rhodium sample located midway between them. The coincidence arrangement was essentially similar to that previously described,[1] with the thin-window (0.001-in. aluminum) NaI(Tl) scintillation detector used to feed the 512-channel pulse-height analyzer.

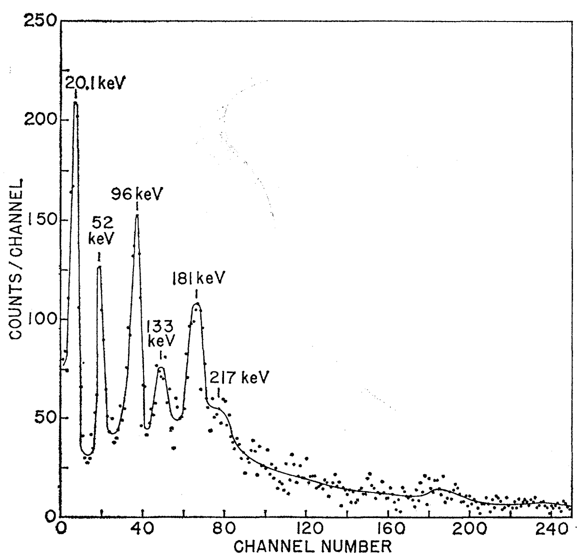

FIG. 4. The low-energy capture gamma-ray spectrum of rhodium in coincidence with the 52-keV line, with a $\frac{3}{32}$-in. tin plus $\frac{1}{64}$-in. copper filter between the rhodium sample and the "fixed" channel NaI(Tl) detector.

[9] J. G. V. Taylor and J. S. Meritt, Phys. in Can. 18, No. 3, 20 (1962).

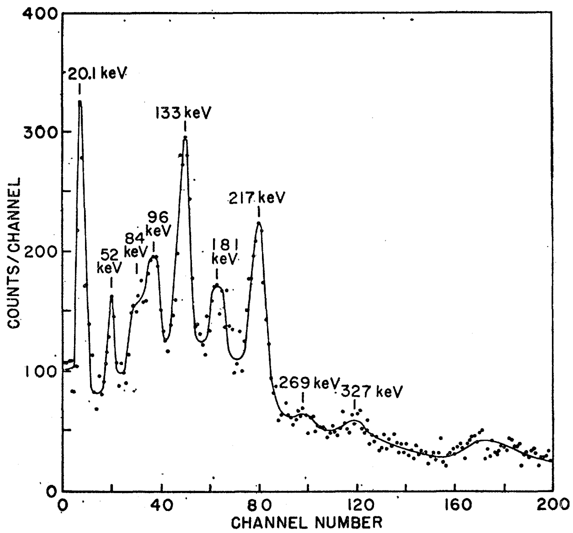

FIG. 5. The low-energy capture gamma-ray spectrum of rhodium in coincidence with the 52-keV line.

To obtain the low-energy Rh^{104} level scheme then, coincidence measurements were made with each of the prominent lines observed in Fig. 3, i.e., with the 52-, the 97-, the 133-, the 181-, the 217-, and the 269-keV line. In each of these coincidence spectra there was also a contribution due to coincidences with the Compton continuum from the higher energy gamma rays, upon which each of these gamma rays sit. Account was taken of this background by observing coincidence spectra with the "fixed" channel set in turn at 52 keV and 96 keV with the $\frac{3}{32}$-in. tin plus $\frac{1}{64}$-in. copper filter located between the sample and the "fixed" channel crystal, and also by observing coincidence spectra with the "fixed" channel set at around 390 keV. In Fig. 4, such a coincidence spectrum is shown where the "fixed" channel was set at 52 keV and the tin and copper filter was located between the sample and the "fixed" crystal. It will be noted that this coincidence spectrum is essentially the same as the "singles" rhodium capture spectrum shown in Fig. 3. In fact, the three background spectra were very similar except for small differences in the total counting rates. To determine the coincidence background completely, it was necessary to know the contribution from the random coincidence spectrum. A measurement of this random coincidence spectrum was made with the "fixed" channel set around 97 keV and a suitable delay line in one of the fast arms of the coincidence circuit. The random coincidence effect proved in practice to be only a small correction factor to the coincidence spectra obtained.

The low-energy rhodium capture gamma-ray spectrum in coincidence with the 52-keV line is shown in Fig. 5. It should be noted that in this spectrum, and the following coincidence spectra shown in Figs. 6 to 9, the appropriate background spectra have not been subtracted out. Because a variety of "fixed" channel widths were used to obtain these coincidence spectra, together with the fact that the counting rates in the "fixed" channel were dependent upon the channel setting and the channel width, the magnitude of the background contribution varied from one spectra to another. In Fig. 5, the 133- and 217-keV lines are found to be in much the strongest coincidence with the 52-keV line while the low-energy shoulder on the 96-keV peak, at approximately 84 keV, was found to be present in all such coincidence spectra obtained. The 52-keV peak seen in Fig. 5 can be accounted for as background. After such a background subtraction, there is still an appreciable 181-keV peak intensity remaining while the 96-keV peak, although appreciably attenuated, still appears to be present.

In Fig. 6, the low-energy rhodium capture gamma-ray spectrum in coincidence with the 96-keV line is shown. The principal feature of this spectrum is the intense 96-keV line. After subtracting the background out, it was found that strong 133- and 174-keV lines still

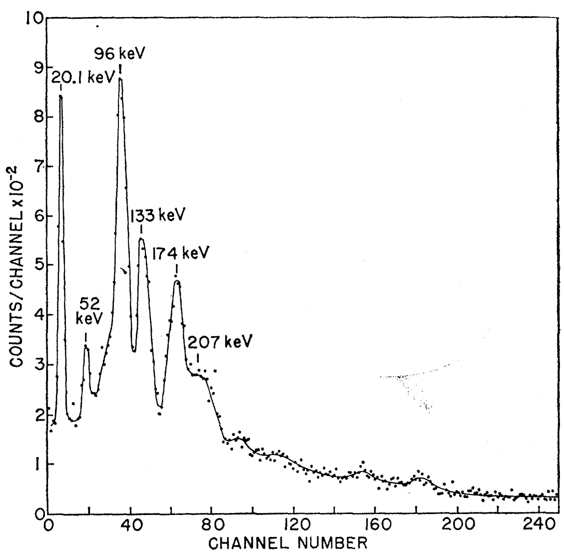

FIG. 6. The low-energy capture gamma-ray spectrum of rhodium in coincidence with the 96-keV line.

remained while the 207-keV line is still somewhat weaker than these two. The shoulder on the lower energy side of the 96-keV peak was observed in all the 96-keV coincident spectra obtained, and since it cannot be accounted for as the iodine *K* x-ray escape peak, it must therefore be due to a line at approximately 83 keV. A small 52-keV peak is still found in this spectrum after the background subtraction and, rather interestingly, the relative intensity of this 52-keV peak, as compared to the 96-keV peak, was observed to decrease as the lower "fixed" channel level was moved to the higher energy side of the 96-keV peak; thus suggesting that the 52-keV peak was due to coincidences with the 84-keV peak observed in Fig. 5.

The low-energy Rh^{104} gamma-ray spectrum in coincidence with the 133-keV line is shown in Fig. 7. It can be seen from this spectrum that the 52- and the 97-keV gamma radiations are in strong coincidence with the

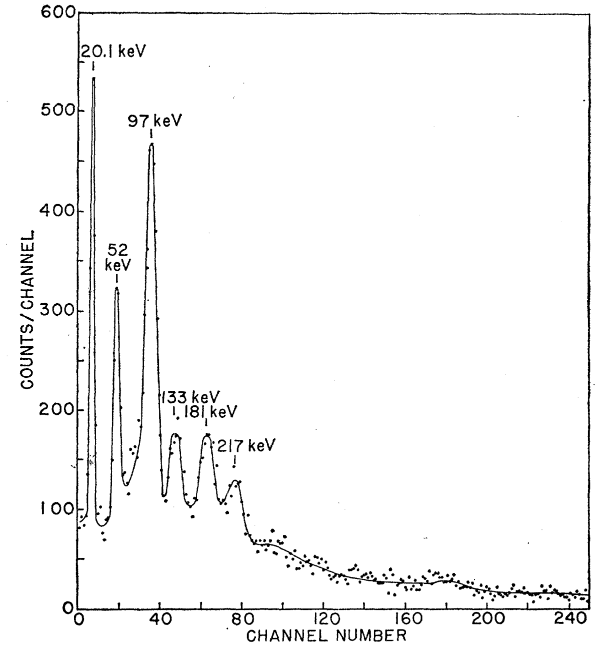

FIG. 7. The low-energy capture gamma-ray spectrum of rhodium in coincidence with the 133-keV line.

133-keV line, while all the other coincident transitions are somewhat weaker. Again, the shoulder on the low-energy side of the 97-keV line in Fig. 7 can only be interpreted as a somewhat weaker transition at around 83 keV. After background subtractions, the 133-, 181-, and 217-keV lines are still present. Since the 52- and 96-keV lines have been observed in Figs. 5 and 6 to be, at most, in a very weak coincidence with each other, it can be concluded from Fig. 7 that there must be at least two (and possibly three) different 133-keV transitions.

The low-energy Rh^{104} gamma-ray spectrum in coincidence with the 181-keV line is shown in Fig. 8. The

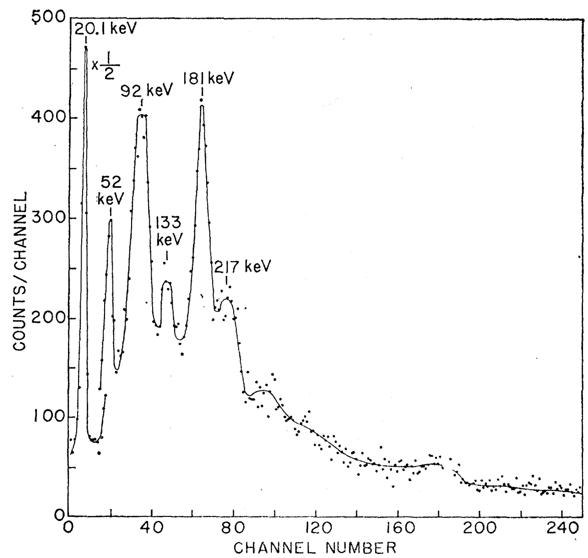

FIG. 8. The low-energy capture gamma-ray spectrum of rhodium in coincidence with the 181-keV line.

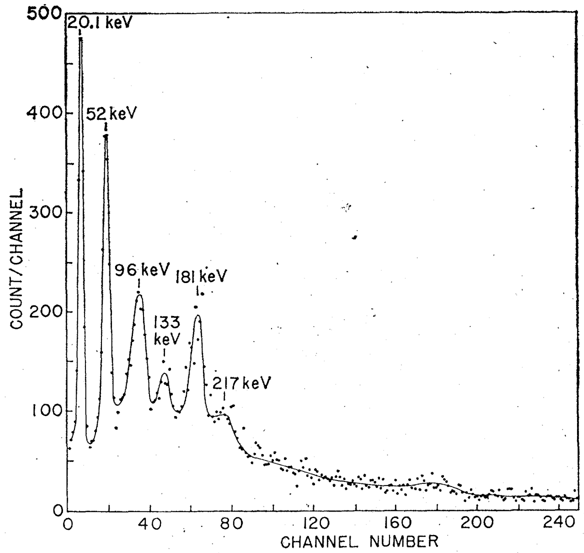

FIG. 9. The low-energy capture gamma-ray spectrum of rhodium in coincidence with the 217-keV line.

most prominent feature of this spectrum is the high intensity of the 92- and 181-keV peaks. The 92-keV peak has a half-width at half-height of 32% and is obviously not a single peak. The most probable explanation for this broad peak at 92 keV is that it is a double peak consisting of two equally strong lines with energies of approximately 86 and 97 keV. The strength of the 181-keV peak indicates that the Rh^{104} level scheme has at least two rather strong 181-keV transitions. After background subtraction, the 52-, 133-, and 217-keV lines are observed to be still prominent. An especially interesting feature of Fig. 8 is the very strong rhodium K x-ray line relative to the intensity of the other peaks. Since the only other feature of Fig. 8 which sets it apart from the other coincidence spectra is the strong 86-keV line, one might suspect that an appreciable part of this rhodium K x-ray peak was contributed by the K internal conversion of the 86-keV transition.

The low-energy rhodium capture gamma-ray spectrum in coincidence with the 217-keV line is shown in Fig. 9. Particular care was taken in obtaining coincidence spectra with this 217-keV line to remove any possible contribution from the 181-keV peak. Towards this end, spectra were taken with the "fixed" channel window set over different parts of the 217-keV peak. The prominent feature of the spectrum shown in Fig. 9 is the strong 52-keV line. After the background subtraction and the correction of the peak intensities for detection efficiencies, relative photopeak efficiencies and transmissions and self absorptions, it is found that the 181-keV transition is somewhat stronger than the 84-, 96-, 133-, and 217-keV transitions.

In all of the coincidence spectra shown in Figs. 5 to 9, there is some evidence for the 269- and 327-keV lines being present after the background subtraction. It is difficult to make definite statements about the relative intensities of these lines however, because of the poor counting statistics generally obtained in this higher energy region. With this limitation, then, it is still interesting to note that the 327-keV peak has approximately the same intensity as the 269-keV peak in the 52-keV coincidence spectrum shown in Fig. 5.

INTERPRETATION

Rather surprisingly, the low-energy coincidence spectra, shown in Figs. 5 to 9, indicate that all the prominent low-energy peaks in the Rh^{104} "singles" gamma-ray spectrum shown in Fig. 3, with the exception of the 52-keV peak, are in fact double and possibly even triple peaks, with both members of the double peak being reasonably strong. The low-energy Rh^{104} level scheme was determined from the cascade transition intensities observed in these coincidence spectra together with the known decay scheme of the Rh^{104m} isomeric level. Throughout this whole analysis, consideration was taken of the way in which angular correlation corrections and the total internal conversion coefficients of the individual transitions would modify these cascade transition intensities. Consequently, the analysis of the data to provide both the Rh^{104} energy levels and the spins and parities of these levels was all inter-related. However, a few of the salient features of this analysis can be discussed in this section:

(1) By far the strongest transitions observed in the 52-keV coincidence spectrum shown in Fig. 5 were the 133- and 217-keV lines. But, in the 133-keV coincidence spectrum shown in Fig. 7 it was observed that the 52-keV transition was much stronger than the 217-keV transition, while from the 217-keV coincidence spectrum shown in Fig. 9, it was observed that the 52-keV transition was much stronger than the 133-keV transition. Consequently, the only interpretation of these results is that there exists Rh^{104} energy levels at 184 and 269 keV, as shown in the proposed Rh^{104} level scheme in Fig. 10.

(2) Since in the 217-keV coincidence spectrum shown in Fig. 9 the 181-keV transition is significantly stronger

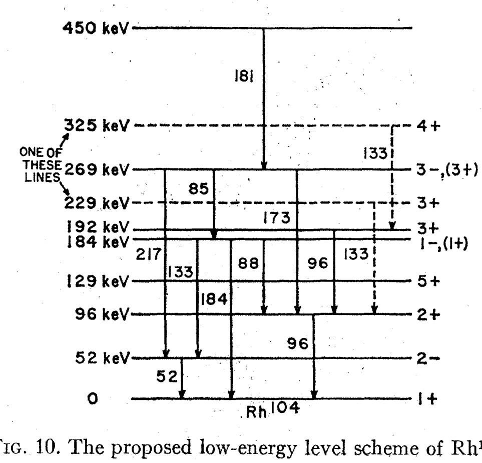

FIG. 10. The proposed low-energy level scheme of Rh^{104}.

than all but the 52-keV transition, it is reasonable to postulate a level at 450 keV from which the 181-keV transition decays to the 269-keV level. Such an assignment finds support from the other coincidence spectra. With this assignment then, the 181-keV transition in the 52-keV coincidence spectrum might be expected to occur via a 181-keV transition to the 269-keV level, with decay occurring from this 269-keV level via a 217-keV transition, or an 85 keV plus a 133-keV cascade, to the 52-keV level. This would account for the 84-keV transition found in Fig. 5.

(3) In the 181-keV coincidence spectrum shown in Fig. 8, the 181-keV line is found to be strongly in coincidence with itself and with an 84-keV transition. Such a 181- to 84- to 184-keV cascade as postulated above would certainly account for the intensity of these lines in Fig. 8. This level scheme would also account for the presence of strong 52-, 133-, and 217-keV transitions in the 181-keV coincidence spectrum. In this respect, it is worth noting that the total transition intensities of the 133- and 217-keV transition are approximately twice that of the 52-keV transition intensity; thus indicating that part of the 133- and 217-keV line intensities are from other transitions of the same energy. Evidence that the 133- and 217-keV lines in the "singles" Rh^{104} gamma-ray spectrum shown in Fig. 3 are double and possibly triple peaks occurred in other coincidence spectra also. From the 133-keV coincidence spectrum shown in Fig. 7, the 133-keV line is seen to be strongly in coincidence with both the 52- and the 96-keV transitions as well as being weakly in coincidence with itself. Since the 52- and 96-keV transitions are only weakly, if at all, in coincidence with each other, this indicates that direct 133- to 52- and 133- to 96-keV cascades exist, with a third 133-keV transition occurring between higher energy levels.

(4) The strength of the 96-keV transition in the 96-keV coincidence spectrum shown in Fig. 6 mitigates against the existence of anything but a direct cascade transition, i.e., from a level at 192 keV to the 96-keV level, and then to the ground state. It should be noted that the accuracy of energy measurements on the 52-, the 96-, and the 133-keV lines, even in these 52- and 96-keV coincidence spectra and especially in the "singles" spectra, such as in Fig. 3, is sufficiently good to rule out the possibility of the 184-keV level and the 192-keV level being one and the same level. The 174-keV line observed in the 96-keV coincidence spectrum can most probably be assigned as occurring in a 181- to 173- to 96-keV cascade from the 450-keV level to the ground state. It has been determined from the 133-keV coincidence spectrum that the 133-keV transition must occur in a direct cascade to the 96-keV transition but, there is no way of determining positively from these data whether the 133-keV transition occurs in a transition from a level at 229 keV to the 96-keV level or from a level at 325 keV to the 192-keV level. Hence, both these levels and transitions are indicated by dashed lines in the level scheme shown in Fig. 10. The weak shoulder on the lower energy side of the 96-keV peak in this 96-keV coincidence spectrum can most probably be accounted for by the 85- to 88-keV cascade from the 269-keV level down to the 96-keV level.

(5) There are several weak lines in these coincidence spectra which cannot be definitely fitted into the level scheme shown in Fig. 10 since they undoubtedly occur in coincidences with higher energy transitions, e.g., the third 133-keV transition. Another example of such a transition is the 207-keV line in the 96-keV coincidence spectrum which could occur in transitions to any one of the 450-, the 269-, the 325-, or the 229-, the 192-, and the 96-keV levels. Again, there is evidence from the 133- and 217-keV coincidence spectra that a second 217-keV transition occurs to either the 269-keV level on the 450-keV level, or some undetermined energy level with energy greater than 269 keV. Finally, although it is tempting to suggest that the 269-keV transition occurs from the 269-keV level to the ground state, it can also be seen that the 269-keV line appears in the coincidence spectra, thus suggesting that it occurs in a transition from a higher level. Of course, the 269-keV line could also be a double peak.

Turning now to the assignment of spins and parities, assignments to the levels up to and including the 129-keV level were made from the previously investigated[1] isomeric decay scheme of Rh^{104} (shown in Fig. 1). Because most of the prominent lines observed in the low-energy rhodium capture gamma-ray spectrum are double and triple peaks the technique utilized by Estulin *et al.*[10] to determine total internal conversion coefficients of transitions in essentially isolated cascades cannot be used. Also the coincidence spectra were sufficiently complex to make K internal conversion coefficient measurements of transitions from individual coincidence spectra generally impractical. Instead, a K internal conversion coefficient analysis was undertaken using all the coincidence spectra in conjunction with the energy level scheme obtained for Rh^{104}. Concerning this analysis, it should be noted that the contribution to the rhodium K x-ray peak from K internal conversion of the higher energy gamma rays is very small and can be neglected. From this analysis it was determined that the 85-keV transition between the 269-keV level and the 184-keV level was an $E2$ transition. With this assignment, it was possible to make an analysis from the 52- and 96-keV coincidence spectra to determine multipolarities of the prominent lines observed in these spectra. From this analysis it was determined that the 133-keV transition from the 184-keV level and the 133- and 217-keV transitions from the 269-keV level must all have either $E1$ or $M1$ multipolarities. Consequently, a spin and parity assignment of $1\pm$ can be made on the 184-keV level with a $3\pm$ assignment on the

[10] I. V. Estulin, A. S. Melioranskii, and L. F. Kalinkin, Soviet Phys.—JETP **13**, 43 (1961), and Nucl. Phys. **24**, 118 (1961).

269-keV level. Also, from the 96-keV coincidence spectrum it was determined that the second 96-keV transition and the 133-keV transition can be either $E1$ or $M1$ transitions. However, the transition intensities in the 133-keV coincidence spectrum seem to indicate that this second 96-keV transition must have an $M1$ multipolarity. That both this 96-keV transition and the 133-keV transition have $M1$ multipolarities would appear reasonable since only these transitions seem to occur with any great probability from the 325- or the 229-keV level and the 192-keV level. This strongly suggests that these levels, together with the 96-keV level and the ground state, have the same proton and neutron configurations. In this case then, these levels would have the spins and parities indicated in Fig. 10, i.e., a 3+ assignment to the 192-keV level and a 3+ assignment to the 229-keV level or a 4+ assignment to the 325-keV level. It is worth noting that if the 325-keV level does exist, one would expect a 196-keV transition to the 129-keV isomeric level with a transition intensity as strong as, or stronger than the 133-keV transition to the 192-keV level. No such 196-keV line is observed in the "singles" spectrum in Fig. 3, although a weak 196-keV line would not be seen due to the presence of the strong 181- and 217-keV lines. The absence of a reasonably strong 196-keV transition though may therefore tend to argue against the existence of the 325-keV level and suggest that the 133-keV transition occurs in a transition from a 229-keV level. Considering now the shell-model proton and neutron configuration assignments to these levels, the recent investigations of the gamma-decay scheme of the 129-keV isomeric state[1] of Rh^{104} have shown that the ground state of Rh^{104} has a $[(g_{9/2})^5]_{7/2}(d_{5/2})^n$ configuration while the 96- and 129-keV levels can have either $[(g_{9/2})^5]_{7/2}(d_{5/2})^n$ or $(g_{9/2})^5(d_{5/2})^n$ configurations. Thus, it can be concluded that the 192- and the 229- or the 325-keV levels also most probably have $[(g_{9/2})^5]_{7/2}(d_{5/2})^n$ or $(g_{9/2})^5(d_{5/2})$ configurations. It is interesting to note in this respect that if, as the previous arguments seem to indicate, the 229-keV level is the correct level assignment, then the level scheme would contain two closely spaced levels at 192 and 229 keV both with 3+ spin and parity assignments. This would suggest then that one level had a $[(g_{9/2})^5]_{7/2}(d_{5/2})^n$ configuration while the other had a $(g_{9/2})^5(d_{5/2})^n$ configuration.

Concerning the 3± and 1± spin and parity assignments on the 269- and 184-keV levels, it is most probable, because of the strength of the 85-keV $E2$ transition between these levels, that these two levels have the same proton and neutron configuration and that other transitions from them require a configuration change of at least one nucleon. Consideration of possible shell-model configurations shows that the negative-parity assignment is most probable since the positive-parity assignment would require a $(g_{9/2})(g_{7/2})$ configuration for these levels. With this configuration one would not expect the strong 217- and 133-keV transitions from these levels to the 52-keV level since both the odd protons and the odd neutrons must change their configurations, and, therefore, these transitions would be strongly hindered, whereas, the transitions to the ground state would require only a neutron configuration change and would be much more probable. With a negative-parity assignment on the levels, however, the most probable configuration would be $(p_{3/2})(d_{5/2})$, which would obey Brennan and Bernstein's[11] modified Nordheim's weak rule with the 1− level lowest [it should be noted that an $(f_{5/2})(d_{3/2})$ configuration would obey the weak rule also, but such a state would require both the odd protons and the odd neutrons to be in different configurations from the ground state and is therefore less likely at these low level energies]. All transitions from the 3- and 1- states, each with a $(p_{3/2})(d_{5/2})$ configuration, would therefore require the proton to change configuration, except for the 85-keV transition between the two levels, thereby accounting for the strength of the 85-keV $E2$ transition. Consequently, the 3− and 1− spin and parity assignments to the 269- and 184-keV levels seem most probable.

If the Rh^{104} energy level scheme determined in these investigations is compared with that obtained by da Silva and Buechner,[7] it can be concluded that, as they suggested, their highest proton group corresponds to the 52-keV level in Rh^{104}. This interpretation seems most probable when it is considered that the 129-keV level, the 96-keV level, and the ground state all have essentially the same odd-proton and odd-neutron configuration, and therefore, it is not apparent why a strong transition should occur to one of these levels and not to the others. With this interpretation then, the lowest levels observed by them have energies 52, 273, 396, 431, 466 keV, and also probably 189 keV; with an error assignment of ±10 keV on these energies. Except for the 396-keV state, levels have been observed at, or near to, all of these energies in this present work. A level at 396 keV could fit quite well into the level scheme shown in Fig. 10 since it could possibly account for the 207-keV line in the 96-keV coincidence spectrum as a transition from the 396-keV level to the 192-keV level. In addition, the 126-keV transition which could possibly occur from this level to the 269-keV level could account for the weak 133-keV peak in the 133-keV coincidence spectrum.

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[11] M. H. Brennan and A. M. Bernstein, Phys. Rev. **120**, 927 (1958).