lated O^{13} beta-decay energy would be greater by 0.2 MeV.

The prediction of the mass of O^{13} was based on the isobaric mass formula and the approximation that the parameter b of this formula is independent of isobaric spin for a given mass number. The extent to which these assumptions are valid may be seen by comparing the value 17.5 ± 0.2 MeV for the Q_{β^+} of O^{13} obtained above to the predicted value of 17.9 MeV.

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Decay of Rh^{105}

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The beta decay of Rh^{105} ($t_{1/2}=35.4\pm0.1$ h) was studied by beta and gamma spectrometry, with 4π beta counting (supported by other methods) for finding absolute intensities. Gamma transitions (keV), with intensities including internal conversion, are 306.3 ± 0.3 (5.4%), 319.3 ± 0.3 (19.4%), 442.7 ± 0.5 (0.04%), and a (38.77 ± 0.07)–(280.5 ± 0.4) cascade (0.17%). The energy separation between the 306.3- and 319.3-keV gammas is 12.97 ± 0.10 keV. From Pd K x-ray intensities, α_K are 5.8 ± 0.6, 0.020 ± 0.004, and 0.012 ± 0.001 for gammas 38.77, 280.5, and (306.3, 319.3) keV, respectively. Several gammas reported by earlier investigators are absent. Population of known Pd^{105} levels at 344 and 489 keV does not occur to an observable extent. The Rh^{105} beta maximum is 550 ± 54 keV; there is no gamma coincident with it. Betas with maxima 249 ± 17 and 133 ± 15 keV are coincident with the main gamma group (280.5, 306.3, 319.3 keV) and the 442.7-keV gamma, respectively. The Pd K x ray is coincident with betas of end point roughly 250 keV. There is no evidence for any Pd^{105} levels below 280 keV, and certainly there are no levels below $\sim$200 keV reached directly by beta transitions. Beta transitions to the indicated 280.5-keV level do not occur ($\leq$0.03%). Inferring spin and parity assignments from these data, we conclude that the decay of Rh^{105} ($\frac{7}{2}+$, $Q_\beta=567\pm20$ keV) takes place by beta transitions to Pd^{105} levels at 0 ($\frac{5}{2}+$, 75%), 306 (probably $\frac{7}{2}+$, 5.4%), 319 ($\frac{5}{2}+$, 19.5%), and 443 ($\frac{7}{2}+$ or $\frac{5}{2}+$, 0.04%) keV; and, via a gamma transition from the 319-keV level, to a level at 280 keV ($\frac{3}{2}+$). The results are discussed in terms of the spherical-potential shell model with phonon states, and the spheroidal-potential (Nilsson) model with rotational states. The Nilsson model gives a better account of the findings than might have been expected, although neither model is completely successful.

INTRODUCTION

In the neighborhood of mass number $A=100$, the so-called even-even nuclei (even Z and N) exhibit spectra which are reasonably well described in terms of quadrupole vibrations[1–4] of the nuclear surface about a spherical equilibrium shape. In contrast, the spectra of odd-A nuclei in this region are relatively complex and not so well understood. It might be possible to think of these odd-A nuclei ($A\simeq100$) in terms of a model[3–7] which separates the motion into two parts, one consisting of the particle states available to the odd nucleon in a spherical potential,[8] and the other consisting of the vibrations responsible for the low states of the neighboring even-even nucleus. The work to be reported in this paper was undertaken primarily to test this model, concerning which the experimental material has been meager up to this time.

A second objective of the present work is to inquire into the possible relevance to the region $A\sim100$ of a model[1,3,4,9–15] which treats the nucleus as being de-

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formed, with particle and rotational states, i.e., the Nilsson model. Some levels of Rh^{103}, Ag^{107}, and Ag^{109} have been described[4,10,16–18] in terms of this model, as have also the angular momenta of odd-odd nuclei[19] in this region. Moreover there is evidence, in the form of magnetic dipole moments (see Table VI of Ref. 9), anomalous nuclear spins[20] of the type $I=j-1$, beta transition probabilities[20] (e.g., the strongly hindered decay of Ru^{103}), and electric quadrupole moments (for instance, the odd-A Cd isotopes),[20–24] that nonspherical equilibrium shapes might well occur in this region; and, in fact, this possibility has been[3,25] predicted. Therefore, we wish to consider the possibility of a new region of deformation ($A\sim105$) with Nilsson particle states and rotational structure. For completeness we mention a modification[26–31] of this model in which the requirement of axial symmetry is relaxed; we shall not attempt an interpretation in terms of this model.

Our work consists of a study of the beta and gamma radiations emitted in the beta decay of 35.4-h Rh^{105} ($Z=45$, $N=60$) to Pd^{105}. One reason for choosing this system is that there already exists a wealth of information on the levels of Pd^{105}, essentially complementary to the information to be expected from Rh^{105} decay, which should increase the chance of providing a useful test of the models. There have been measurements of the Pd^{105} ground-state nuclear spin[32] ($I=\frac{5}{2}$) and magnetic dipole moment ($\mu=-0.6$ nm),[33] and much information about the excited states has been accumulated by Coulomb excitation,[34–37] by deuteron stripping and pickup reactions[38] on Pd^{104} and Pd^{106}, by photonuclear reactions (γ,γ') and $(\gamma,n\gamma')$ on Pd^{105} and Pd^{106}, respectively,[39,40] and by resonance fluorescence[41] methods. Finally, the radioactive decay of Ag^{105} to Pd^{105} has been studied recently[42] in great detail.

The decay of 35.4-h Rh^{105} has been studied[43–51] several times. Most of these studies indicate a total decay energy of about 565 keV, a half-period of 35 to 36.5 h, and the presence of a 300- to 320-keV gamma ray in some (0%,[43] 4%,[47] 8%,[44] 10%,[46], or 25–30% [48,49]) of the disintegrations. On further details there is widespread disagreement. Some of this disagreement undoubtedly has to do with the relatively primitive instrumentation with which some of the earlier measurements had to be made; but a large part of the trouble appears to stem from radioactive contamination, which can be avoided only by adequate chemical procedures.

In any case it has been clear for some time[42] that there must be some transitions not yet reported, a prediction confirmed by us and also by Karlsson, Bergman, and Scheuer.[52] In general, our results substantiate those of Refs. 48, 49, and 52, but disagree in some respects with the rest.

EXPERIMENTAL

We have measured the energies, intensities, and time-coincidence relationships of the radiations associated with Rh^{105} decay, by means of NaI(Tl) and lithium-drifted germanium crystals (for gammas), plastic phosphors (for electrons), a Xe-CH_4-filled proportional

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counter (for x rays), and gas-flow (CH_4) proportional counters of 4π and end-window types. Associated electronics included conventional amplifiers, a fast-slow coincidence unit,[53] and a multichannel analyzer.

Spectrum measurements normally were carried out inside a large shield. Beryllium absorbers were used to prevent betas from reaching the gamma and x-ray counters. For the coincidence measurements, scattering between detectors was prevented by appropriate baffles.

In the coincidence work, the accidental-coincidence spectrum appropriate to the total coincidence spectrum was evaluated and subtracted from the latter in every case. The procedure was to accumulate first a spectrum with an arbitrary 0.4-μsec delay for a certain period of time t_1, during which a certain number of accidental coincidences were recorded (0.4 μsec is sufficient to destroy the timing between true coincidence events); and then with the proper timing restored to accumulate a coincidence spectrum for that period of time t_2 during which the same number of accidental coincidences should occur as occurred during t_1; the difference between the two spectra is the true coincidence spectrum. The relationship between t_1 and t_2 is

$$e^{-2\lambda t_2}=2-e^{2\lambda t_1}, \qquad (1)$$

where λ is the decay constant $(\ln 2)/t_{1/2}$. Sources employed were weak enough to keep the accidental-coincidence rate reasonably low (e.g., below $\frac{1}{10}$ the true-coincidence rate) for reasonable resolving times (e.g., 10^{-7} sec).

For measurements of absolute gamma intensities, the NaI(Tl) crystals were calibrated with sources standardized by means of the 4π beta counter or sources from the National Bureau of Standards. A Cd^{109} source was used for calibration at 22.6 keV, the emission rate of its 22.6-keV line (Ag K x ray) having been determined with a thin NaI(Tl) crystal ($\frac{1}{8}$ in. thick$\times 1\frac{1}{8}$ in. diam). (The rate found agrees roughly with that obtained from the assumption that the Ag K x ray is 23.8 times as intense[54] as the 88-keV line.)

In each hemisphere of the 4π beta-counter chamber, the anode wire was run between the prong ends of a Y-shaped center post; this gives wider voltage plateaux than the usual loop configuration. Source backings were VYNS films[55] 5–10 μg/cm^2 thick, with $\sim$3 μg/cm^2 gold on both sides.

The Pilot B phosphors[56] used for beta spectrometry (1 in. height$\times 1\frac{1}{4}$ in. diam) had a well $\frac{3}{8}$ in. deep, $\frac{1}{4}$ in. top diam and $\frac{3}{8}$ in. bottom diam, all surfaces polished. Aluminum-coated Mylar was stretched over the front face and pulled down over the phototube, and a hole was punched over the mouth of the well. The source, mounted on a similar piece of Mylar, was laid over the well with the source side inward. This arrangement gave resolutions as good as 12.2% FWHM (full width at half-maximum) at 624 keV. Sources for measurement of gamma spectra, etc., were generally mounted on similar films.

Sources for measurement of Pd L x rays with the Xe-CH_4-filled proportional counter were mounted between the pole faces of a magnet which prevented betas from reaching the counter. This obviated the use of beryllium beta absorbers, which would also have stopped the L x rays.

For total-absorption gamma spectrometry, a NaI(Tl) well crystal (2 in. height$\times 1\frac{3}{4}$ in. diam) was used. The well ($1\frac{1}{2}$ in. deep$\times\frac{3}{4}$ in. diam) was lined with enough plastic ($\geq$230 mg/cm^2) to stop the betas. A light pipe was necessary for good resolution.

Other NaI(Tl) crystals used were $\frac{1}{16}$ in. height $\times 1\frac{1}{2}$ in. diam (5-mil Be window), $\frac{1}{8}$ in. height$\times 1\frac{1}{8}$ in. diam (1-mil Al window, 1-in. quartz light pipe), $\frac{1}{2}$ in. height$\times 1\frac{1}{2}$ in. diam (1-mil Al window), and 3 in.$\times$3 in.

To produce the Rh^{105}, ruthenium powder (Fisher Scientific Co.; stated purity 99.8% minimum; Fe 300 ppm, Rh 300 ppm, Pd 200 ppm, Au 100 ppm, all others $<$100 ppm; no detectable Os, Ir, or Pt, i.e., $\sim$1 ppm or less) was irradiated for up to 1 h with neutrons in the Ford Nuclear Reactor of the Phoenix Memorial Laboratory, University of Michigan. This produced 4.4-h Ru^{105} by the $Ru^{104}(n,\gamma)Ru^{105}$ reaction. After chemical steps to purify the Ru activity, the Rh^{105} decay product was allowed to grow in for some 12 h and then a separation of carrier-free Rh^{105} was made. The final solution (or portion thereof) was deposited on a backing (previously treated with insulin solution to promote even distribution) and dried under vacuum. Interference from 57-min Rh^{103m}, produced by $Ru^{102}(n,\gamma)Ru^{103}(\beta)Rh^{103m}$, was avoided by waiting a while after the Rh separation before starting the measurements.

The basis for the chemical procedures, for the most part, is found[57,58] in the literature. However, it was necessary to take steps to remove iridium activity produced by neutron-capture reactions of iridium impurity in the ruthenium target. These steps[59] are (1) to have iridium carrier present in the still during the usual[57] distillation of RuO_4 from $HClO_4$ (otherwise about half of the iridium comes over), and (2) to precipitate iridium by alkaline oxidation to IrO_2 with $NaBiO_3$.

The procedure for isolating the Ru^{105} activity[59] is to dissolve the metal in NaOH-NaOCl solution, add Ir^{III} carrier, then $NaBiO_3$, heat to precipitate IrO_2, make a $ZrO_2\cdot xH_2O$ scavenge by adding Zr^{IV} carrier, repeat the

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IrO_2 and $ZrO_2 \cdot xH_2O$ steps, precipitate RuO_2 (and Ru_2O_3) with ethanol, dissolve the RuO_2 in HCl, add Ir^{III} carrier, and distill from $HClO_4$ into cold HCl.

The procedure for isolating the Rh^{105} daughter from this HCl solution is to make another $HClO_4$ distillation, keeping now the residue, drive off all traces of Ru and then of $HClO_4$, take up the residue (Rh^{105}) in 6*N* HCl, and pass this through a Dowex-50 cation exchange column (to remove extraneous matter). Alternatively, we leave a trace of $HClO_4$ instead of driving it all off, take up the residue in water and neutralize it with NH_3, absorb the Rh^{105} on S & S filter paper and elute with 1*N* HCl; this procedure[60] gives more solid in the final source, however.

Sources prepared in the above manner and counted in the gas-flow beta proportional counter exhibited no significant deviation from the Rh^{105} half-period for four weeks (19 half-periods). The chief contaminant observed is ruthenium (observed as Ru^{103}), whose presence is due to its incomplete removal in the last distillation. Typically the ruthenium decontamination in the last distillation is $>10^5$-fold. Gamma spectra of samples two to five weeks old reveal 40-day Ru^{103} activity corresponding to 1.3×10^{-6} Ru^{103} disintegration per Rh^{105} disintegration in the initial Rh^{105} source. No osmium contamination was observed; the upper limit on any possible 129-keV gamma (15-day Os^{191}) implies in turn (if one uses reasonable[20] neutron-capture cross sections for Os^{190} and Os^{192}) that no more than 9×10^{-7} Os^{193} ($t_{1/2}=32$ h) disintegrations per Rh^{105} disintegration could have been present in the Rh^{105} samples at commencement of measurements. No other appreciable contaminants were observed. Iridium was absent (decontamination $>10^6$-fold).

The transitions which we shall report are all of sufficient intensity that their association with the decay of Rh^{105} may be regarded as certain, especially since they exhibit the correct half-period and their relative intensities are constant from one experiment to another.

RESULTS

The NaI(Tl) gamma spectrum (Fig. 1) shows a hitherto unreported gamma ray at 442.9 ± 1.0 keV, of intensity 0.00161 ± 0.00004 times the intensity of the main peak. It also shows that the main peak (316.6 ± 0.3 keV) consists of more than one component; FWHM is 11.3% whereas 10.5% would be expected for a single line at this energy. (The small peak at low energy is the Pd *K* x ray; its intensity is 0.014 ± 0.001 times that of the main peak.)

Gamma-gamma coincidence experiments (to be described later) were used to assess the intensity of the 280-keV component shown in Fig. 1. This was subtracted from the main peak and the remainder was

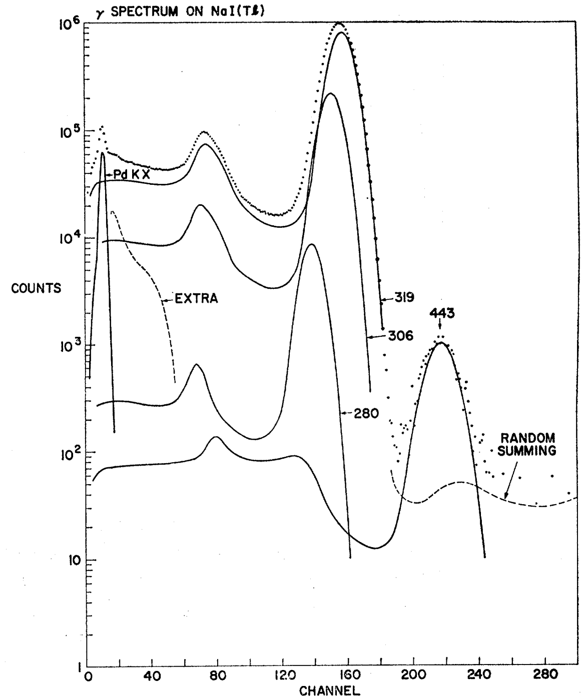

FIG. 1. Gamma spectrum 10.0 cm from 3-in.×3-in. NaI(Tl) crystal. Dotted "extra" component is mainly bremsstrahlung.

analyzed, assuming a two-component remainder and using for the line shape the 320.3-keV gamma[61] from Cr^{51} decay. The analysis was tedious but straightforward, and gave components $306.3_{-1.6}^{+3.1}$ and 319.1 ± 0.6 keV (relative to $Cr^{51}\equiv320.3$ keV), the energy difference being $12.8_{+3.0}^{-1.5}$ keV, and the lower energy component being $0.27_{-0.11}^{+0.15}$ times as intense as the higher energy one.

In support of these results, we show in Fig. 2 a gamma spectrum obtained later with a lithium-drifted germanium detector. The gamma energies and relative intensities from this spectrum are 280.6 ± 0.4 (0.0068 ± 0.0005), 306.4 ± 0.4 (0.218 ± 0.017), 319.4 ± 0.4 (0.775 ± 0.017), and 442.7 ± 0.6 (intensity not determined) keV. The energy difference between the 306.3- and 319.3-keV gammas is 12.97 ± 0.10 keV. Final energy values for the three highest-energy gammas can now be inferred from the combined NaI(Tl) and Ge gamma spectra: 306.3 ± 0.3, 319.3 ± 0.3, and 442.7 ± 0.5 keV (Table I).

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[61] We measured the energy of this gamma as 320.28 ± 0.66 keV by comparison with lines of known energy (from Hg^{203}, Sn^{113}, Na^{22}, and Cs^{137} sources). The result is at variance with the values commonly given, which average about 323 keV (see Ref. 20). However, recent measurements by D. H. White, W. John, B. G. Saunders, and R. W. Jewell [Nucl. Phys. (to be published)] with a bent-crystal spectrometer give 320.18 ± 0.21 keV, in excellent agreement with our number; and recent measurements by R. L. Robinson and P. H. Stelson [Bull. Am. Phys. Soc. **10**, 245 (1965)] give 319.8 ± 0.3 keV. (We also measured the energy of the prominent gamma associated with decay of 40-day Ru^{103} and found 497.7 ± 0.4 keV.)

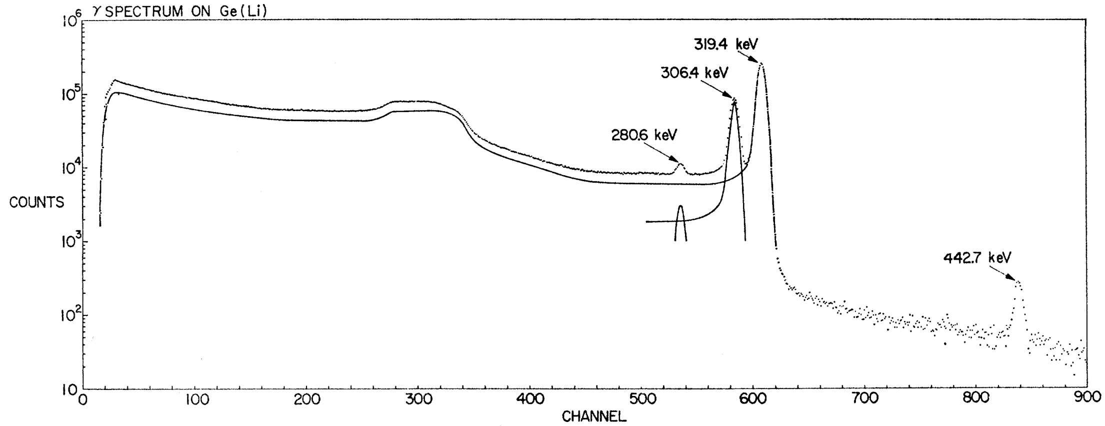

FIG. 2. Gamma spectrum obtained with Li-drifted Ge detector. Energy scale is about 0.536 keV per channel.

The energies (306.3 and 319.3 keV) and relative intensities of the two prominent gammas are in excellent agreement with the results of Karlsson *et al.*[52] who, however, because of the low efficiencies inherent in external and internal conversion electron measurements, did not observe the transitions at 280 and 443 keV.

Gating the NaI(Tl) coincidence apparatus on the main peak, we find that the gamma spectrum in coincidence (Fig. 3) shows peaks at 21.6 (Pd K x ray) and 38.77±0.07 keV (the mean of this experiment and a later proportional spectrometer measurement). Gating on the Pd K x ray (Fig. 4), and then on the 38.8-keV gamma, we find both radiations to be in coincidence with a 280.4±0.9-keV gamma but not with each other (i.e., the 38.8–x coincidence rate is $<1/7$ what would have been expected for a true x–38.8–280.4 three-step cascade). This 280.4-keV gamma is taken to be the same as the 280.6-keV gamma seen with the Ge detector. Combining all the data, a mean of 280.5±0.4 keV

TABLE I. Partial synopsis of experimental results.

Gamma intensities given below (% of the Rh^{105} disintegrations) do *not* include internal conversion.	
$t_{1/2}$	35.4±0.1 h
γ_1	Pd K x ray, 0.34%
γ_2	38.77±0.07 keV, $\alpha_K=5.8$
γ_3	280.5±0.4 keV, 0.17%, $\alpha_K=0.020$
γ_4	306.3±0.3 keV, 5.4% } $(\alpha_K)_{av}=0.012$
γ_5	319.3±0.3 keV, 19.1% } $(\alpha_K)_{av}=0.012$
γ_6	442.7±0.5 keV, 0.040%
γ_1-γ_3 cascade	0.10%
γ_2-γ_3 cascade	0.022%
$E_{\gamma_5}-E_{\gamma_4}$	= 12.97±0.10 keV
$\frac{\text{Intensity of } \gamma\gamma \text{ cascades of total } E\sim 443}{\text{Intensity of } \gamma_6}$	<0.017
Q_β	567±20 keV
β	~550 keV to Pd^{105} ground state, 75%
β	~249 keV coincident with γ_{3-5}, 24.6±0.7%
β	~133 keV coincident with γ_6, 0.04%

(Table I) is derived. From these experiments, the intensities of the coincidences relative to the main peak are 0.00091±0.00014 for the 38.8–280.5 cascade and 0.0042±0.0006 for the Pd K x–280.5 cascade.

Assuming 0.793 for the K-shell fluorescence yield[62] in Pd, the K-shell internal conversion coefficient α_K of the 38.8-keV transition is 5.8±0.6, which establishes it as a magnetic dipole ($M1$) transition (theoretical[63] $\alpha_K=5.3$). Similarly, the α_K of the 280.5-keV transition may be calculated from the gamma coincidence spectrum triggered on the Pd K x ray (Fig. 3) as follows: The ratio between the intensity of the (K x)–(K x) coincidence and the intensity of the (K x)–280.5 coincidence is 0.032±0.003, after correction for the x rays in Fig. 3 which are triggered by that slice of the 280.5-keV gamma response which falls within the window of the gating side (x-ray side) of the coincidence unit (i.e., after correction for x rays triggered on the Compton of the 280.5-keV gamma). This ratio is equal to $2f\alpha_K$, where f is the K-shell fluorescence yield (0.793), whence it follows that α_K of the 280.5-keV transition is 0.020 ±0.004; this establishes the transition as $M1$ (theoretical[63] $\alpha_K=0.021$ for $M1$, 0.031 for $E2$).

The intensity of the Pd K x ray not involved in gamma-gamma coincidences is found by subtraction to be 0.010±0.001 relative to the main peak, giving an effective α_K of 0.012±0.001 for the composite peak, suggesting that at least the more intense component, 319.3 keV, is $M1$ (theoretical[63] $\alpha_K=0.014$ for $M1$, 0.021 for $E2$). On the reasonable hypothesis that the 38.8- and 319.3-keV gammas both originate from a Pd^{105} level at 319.3 keV, the relative intensities of the two are about what one would expect if they were both $M1$ transitions. The assignment $M1$ for the 319.3-keV transition is in agreement with Karlsson *et al.*,[52] who

[62] A. H. Wapstra, G. J. Nijgh, and R. van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959).

[63] M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, 1958).

show clearly that both the 306.3- and 319.3-keV transitions are primarily $M1$.

Using for the 38.8-keV gamma a total α of 6.7 (estimated by using our experimental α_K value and Rose's[63] tabulations of α_L and α_M), the intensity of the 280.5-keV gamma ray (unconverted) in coincidence with the 38.8-keV *transition* (both converted and unconverted) is 0.0070 ± 0.0011 times the intensity of the main peak.

Combining this number with the total 280.5-keV gamma intensity as measured with the lithium-drifted germanium detector, we find that the intensity of the 280.5-keV gamma *not* included in the 38.8–280.5 cascade is $(-)0.0002\pm0.0012$ times the intensity of the main gamma peak, i.e., zero within the uncertainty, and no more than 0.0010 in any case.

The beta spectra in singles, in coincidence with the main peak, and in coincidence with the 442.7-keV gamma ray show end points at 550 ± 54, 249 ± 17, and 133 ± 15 keV, respectively. These data show that the main peak has to do, at least primarily, with Pd^{105} levels

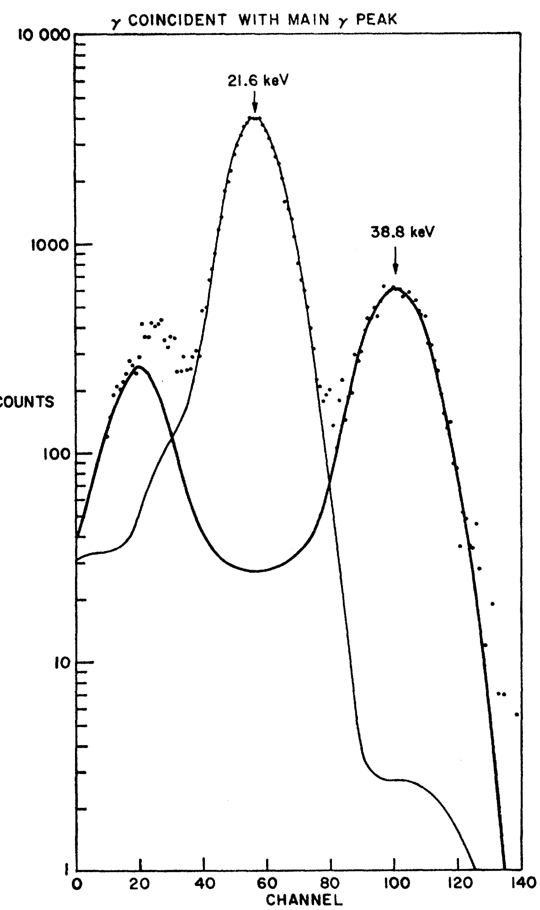

FIG. 3. Gamma spectrum in coincidence with main gamma (230- to 415-keV) peak. Gating crystal is ½-in.×1½-in. NaI(Tl), 290 mg/cm² Al absorber. Gated spectrum is viewed by ⅛-in.×1⅛-in. NaI(Tl), 370 mg/cm² Be absorber. Crystals are placed coaxially, with source in between over a small aperture in a "graded" (Pb, Cd, Cu, Al) antiscatter shield. Bremsstrahlung and other secondary effects have been subtracted.

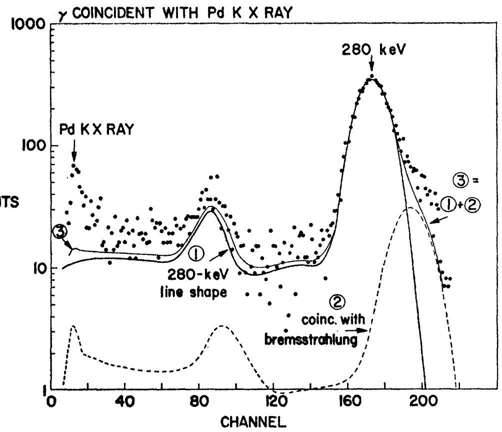

FIG. 4. Gamma spectrum in coincidence with Pd K x ray. Gating crystal is ⅛-in.×1⅛-in. NaI(Tl), 379 mg/cm² Be absorber, 3 cm from source. Gated spectrum is viewed by 3-in.×3-in. NaI(Tl) 7.6 cm from source. Crystal axes pass through source at included angle 112°. Graded shield blocks straight-through paths between crystals. Curve ② is the contribution from main-peak gammas triggered by bremsstrahlung. Curve ③≡①+② fits the experimental points (dots) if allowance is made for Pd K x–Pd K x coincidences (from $K_{38.8}$–$K_{280.4}$ coincidences), for bremsstrahlung triggered by Compton of the main peak, and other effects.

near 300 keV; and that the 442.7-keV gamma ray comes from a Pd^{105} level at that energy. Gating on the Pd K x ray, we observe a beta spectrum of endpoint about 250 keV and a conversion electron of energy about 295 keV, as expected (K conversion of 306- and 319-keV gammas).

Reversing the procedure and gating on betas, it is found that the gamma spectrum coincident with the gross beta spectrum is essentially the same as the singles gamma spectrum, indicating that all the gamma transitions are prompt ($<10^{-7}$ sec). As we gate on successively higher energy portions of the beta spectrum, the coincident gamma spectrum behaves as expected, i.e., the 442.7-keV peak disappears first, etc. As the discriminator setting approaches 300 keV, the gamma response fades out, showing that there are no levels below $\sim$200 keV in Pd^{105} which are populated directly by beta transitions. Thus it seems reasonable that the order of the 38.8–280.5-keV gamma cascade is as written rather than the inverse. Although this point is admittedly not proved, we consider it established beyond reasonable doubt, especially in view of the earlier mentioned branching ratio between the 38.8- and 319.3-keV $M1$ gamma rays, and in view of the reported existence[42] of a Pd^{105} level at 280.4 keV.

A total decay energy Q_β of 567 ± 20 keV was estimated by combining the above-reported beta and beta-gamma-coincidence energy measurements with a beta absorption curve using plastic absorbers and an end-window proportional counter. This result is in good agreement with most other authors[20,43,45,46,48,49,52]; it is in disagreement[51] with Rosen.

Beta-beta coincidence measurements were carried out in order to gather information on conversion electrons coincident with betas. The results corroborated our other findings. The (L, M, etc.) conversion of the 38.8-keV transition was too weak to detect, indicating low α_{LM}, consistent with an $M1$ transition. The K conversion lines of the main peak were observed, unresolved, at 294 keV; the shape indicated high (>4) mean α_K/α_{LM}, as expected.

By now it is clear that the decay of Rh^{105} populates Pd^{105} excited states at about 280, 306, 319, and 443 keV. It remains to be settled whether other known levels at 344 [42] and 489 keV [39,40] are also populated, as well as whether there are, in addition to the 38.8-keV transition between the 280- and 319-keV levels, other transitions between excited levels.

By taking gamma spectra gated on the main gamma peak, it was ascertained that, relative to the intensity of the main peak, the intensity of any 64–280 cascade (the mode by which the 344-keV level[42] in Pd^{105} depopulates some 63% of the time) is less than 1.6×10^{-5}, and the intensity of any 183–306 cascade (the mode of depopulation of the 37-μsec level[40] at 489 keV in Pd^{105}) is less than 6×10^{-6}. Using known information[42] about conversion coefficients for the 64-keV transition, the branching between the 64- and 344-keV transitions from the 344-keV level, and the conversion coefficients of the 183-keV transition from the 489-keV isomeric level, we conclude that in Rh^{105} decay the frequency of formation of these two levels, relative to the intensity of the main gamma peak, is less than 9×10^{-5} for the 344-keV level and less than 8×10^{-6} for the 489-keV level.

These gamma-gamma coincidence experiments did reveal the possible presence of a gamma of energy about 139 keV in coincidence with something in the main peak, and about 0.007 times as intense as the 442.7-keV gamma. This could be the 137-keV transition between the Pd^{105} levels at 443 and 306 keV, but the low intensity prompts concern that the cascade might be associated with a contaminant; one might suspect 32-h Os^{193}, which has a 139–322 cascade in 1.7% of its disintegrations, but the amount of Os^{193} which could be present (see earlier) should be 200 times too small to permit the cascade to be assigned to Os^{193} contamination. Still, the possibility cannot be dismissed that the cascade does result from a contaminant of some sort.

Transitions from the 443-keV level to the levels at 280, 319, and 344 keV were undetectable in the gamma-gamma coincidence experiments. Cascades from the 443-keV level via the levels at 280 and 319 keV are, respectively, at most perhaps 0.005 and 0.006 times as intense as the 442.7-keV crossover transition. The gross cascade intensity from the 443-keV level via *all* routes is at most 0.017 times the intensity of the 442.7-keV gamma.

This surprisingly low cascade/crossover ratio (at least three times lower than expected) was confirmed by attempts to observe coincidence summing, using the NaI(Tl) well crystal. Measurements were made in the well and 10 cm above the crystal; source strengths were adjusted to give equal (and small) random summing effects in both positions; and the two positions were carefully calibrated at the appropriate energies. The total cascade/crossover ratio from the 443-keV level was found by this summing experiment to be 0.00, with an upper limit 0.024. From all these results, then, the total cascade/crossover ratio from the 443-keV level appears to be less than 0.017.

No evidence was observed for any 230–275-keV gamma cascade reportedly[20] excited in Coulomb excitation.

Efforts by gamma-gamma coincidence experiments gating on the main peak, and by singles spectrometry with the Xe-CH_4 proportional counter, failed to reveal evidence for a 25.8-keV transition between the 306- and 280-keV levels, or for a 13.0-keV transition between the 319- and 306-keV levels. The upper limit, relative to the intensity of the main gammas, for a 25.8-keV gamma ray is 0.00006 and for a 13.0-keV gamma ray is 0.00018.

The proportional-counter spectra showed what appear to be Pd L x rays of intensity 0.20 ± 0.05 times that of the Pd K x ray (based on 0.0505 for the L/K x-ray intensity ratio from a Cd^{109} source[20]); this intensity is perhaps higher than what might have been expected (~0.10). Resolution between the Pd K_α and K_β x rays was obtained, and the information is consistent with the proposition that there are no gamma rays at those energies, other than the K x rays. The measured $E_{K\alpha}$ was 21.2 keV; expected[64] is 21.12 keV.

There are several transitions reported by other authors which we sought but could not detect. These include gammas of 80,[46,50] 157,[46] and 164 keV,[50] and gamma-gamma cascades[51] (keV) 220–315, 308–315, 415–315, and 550–315. Our data show respective maximum intensities 3×10^{-3}, 2×10^{-3}, 2×10^{-3}, 1.7×10^{-5}, 4×10^{-5}, 2.2×10^{-5}, and 1.9×10^{-5}, relative to the main gamma intensity. Further, no evidence was found for a reported[51] 420-keV beta transition.

The absolute intensities of the gamma rays, i.e., the number emitted per disintegration of Rh^{105}, were determined by three methods, as follows.

First method: Absolute disintegration rates of Rh^{105} sources were determined with the 4π gas flow beta counter. The area of the main gamma peak for each source was then determined with a calibrated 3-in. ×3-in. NaI(Tl) crystal. From these data, the absolute intensity of the main gamma group can be calculated directly, and thence the individual gammas.

Second method: Separated isotope Ru^{104} was irradiated to give a Ru^{105} source free of other ruthenium species. The area of the full-energy peak of the 720-keV

[64] This was calculated from data in Ref. 62.

gamma ray, which occurs in $(50\pm2)\%$ [65–67] of the disintegrations of Ru^{105}, was measured as before. At a suitable later time, after the Ru^{105} was essentially gone, the area of the main peak from the Rh^{105} daughter activity was measured. Using the measured half-periods of Ru^{105} and Rh^{105}, the fraction of Rh^{105} disintegrations producing the main gammas could be calculated. The half-period of Ru^{105} was determined as 4.39 ± 0.10 h by following the 720-keV gamma peak, and the half-period of Rh^{105} was determined as 35.41 ± 0.10 h by least-squares analysis of two experiments using the end-window gas flow beta counter.

Third method: The disintegration rate was determined from the coincidence rate between betas and main-peak gammas, using calibrated detectors (Pilot B for betas). A gamma spectrum taken at about the same time gave the main gamma emission rate and, thereby, the number per disintegration.

The three methods give excellent agreement and show that the absolute intensity of the main group of gamma rays (280.5, 306.3, 319.3 keV) is 0.246 ± 0.007 per disintegration. This result agrees with Refs. 48, 49, and 52, but is in serious disagreement with most of the others.[43–47,50]

From the data thus far presented, making allowance for internal-conversion processes, the absolute beta-transition intensities are:

to Pd^{105} ground state 0.750 ± 0.007,

to 280-keV level ≤ 0.0003,

to 306-keV level 0.054 ± 0.004,

to 319-keV level 0.195 ± 0.004,

to 344-keV level $\leq 2.3\times10^{-5}$,

to 443-keV level 0.00040 ± 0.00001,

and

to 489-keV level $\leq 2.0\times10^{-6}$.

The respective $\log ft$ values are 5.7, ≥ 8.2, 5.8, 5.1, ≥ 8.7, 6.8, and ≥ 8.5. Table I lists our major findings.

DECAY SCHEME

Refer to Fig. 5 in what follows. The Pd^{105} ground state has spin $\frac{5}{2}$ with even parity[20,32,33,38] ($I\pi=\frac{5}{2}+$). The beta decay to this state from Rh^{105} involves a spin change ΔI of 0 or 1 (transitions with ΔI greater than this have no known cases[68] with $\log ft$ lower than 6.8). Thus I of Rh^{105} is $\frac{3}{2}$, $\frac{5}{2}$, or $\frac{7}{2}$. The gamma transitions to the Pd^{105} ground state from the levels at 280 and 319 keV are $M1$ ($\Delta I\leq 1$, no parity change) and thus we are restricted to $I\pi=(\frac{3}{2}, \frac{5}{2}, \text{or } \frac{7}{2})+$ for the two levels. This in turn means that the parity of Rh^{105} is even, since the beta transition to the 319-keV Pd^{105} level is shown, by the low $\log ft$ value, to be allowed ($\Delta I\leq 1$, no parity change). In summary, Rh^{105} and the 280- and 319-keV Pd^{105} levels are all limited to $(\frac{3}{2}, \frac{5}{2}, \text{or } \frac{7}{2})+$.

The beta transition from Rh^{105} to the 280-keV Pd^{105} level should be allowed and therefore observable if the spin change were less than two units. Since the transition was not observed ($\log ft\geq 8.2$), the spins of Rh^{105} and the 280-keV Pd^{105} level evidently must differ by more than 1 unit, and therefore one spin is $\frac{3}{2}+$ and the other $\frac{7}{2}+$. But the 319-keV Pd^{105} level is connected to Rh^{105} by an allowed beta transition and to the 280-keV Pd^{105} level by a $M1$ transition; therefore the 319-keV Pd^{105} level is $\frac{5}{2}+$ in any case.

This argument (proving $\frac{5}{2}+$ for the 319-keV level) can be attacked on the grounds that there are known cases[68] of allowed transitions with $\log ft$ values upwards of 8.2 and that therefore the spins of Rh^{105} and the 280-keV level could conceivably differ by 0 or 1 unit after all. Nevertheless, there exists corroboration for the $\frac{5}{2}+$ assignment, as will be seen.

We can now establish I for Rh^{105} and the 280-keV Pd^{105} level, simply by noting that the latter cannot be $\frac{7}{2}+$ because it is populated[42] by electron-capture transitions from Ag^{105} ($I\pi=\frac{1}{2}-$) with $\log ft\simeq 7.8$ (for $\frac{1}{2}-\rightarrow\frac{7}{2}+$, $\log ft$ would be about 18). Thus, of the two possibilities ($\frac{7}{2}+$ and $\frac{3}{2}+$) consistent with the Rh^{105} decay data, $\frac{3}{2}+$ must be assigned to the 280-keV Pd^{105} level and $\frac{7}{2}+$ to Rh^{105}. (Supporting this, the Ag^{105} decay data[42] of themselves furnish positive evidence that the 280-keV Pd^{105} level is $\frac{3}{2}+$ and not, for example, $\frac{5}{2}+$.)

Further support for assigning $\frac{7}{2}+$ (rather than $\frac{3}{2}+$) to Rh^{105} derives from the 344-keV Pd^{105} level which appears (from Ag^{105} decay[42]) to be $\frac{1}{2}+$. This level is not formed in Rh^{105} decay ($\log ft\geq 8.7$), and thus $\frac{3}{2}+$ for Rh^{105} is virtually ruled out. (This would still hold if the 344-keV level were $\frac{3}{2}+$, which is the only conceivable alternative.)

Angular correlation measurements[69,70] of the 64–280 gamma cascade from the 344-keV level have given contradictory results for the 344- and 280-keV levels, one report[69] giving $\frac{1}{2}$ and $\frac{3}{2}$, respectively, the other[70] $\frac{5}{2}$ and $\frac{7}{2}$. Both levels are known[42] to have even parity. But the absence of beta decay to the 344-keV level from Rh^{105} ($\frac{3}{2}+$, $\frac{5}{2}+$, or $\frac{7}{2}+$) means that the 344-keV level can hardly be $\frac{5}{2}+$. Thus we conclude, as do Suter *et al.*,[42] that the former results are probably correct: $\frac{1}{2}+$(344) and $\frac{3}{2}+$(280).

The 306-keV Pd^{105} level is probably $\frac{7}{2}+$ although the evidence is not all that could be wished. The beta transition from Rh^{105} ($\frac{7}{2}+$) to this level involves ΔI not over 1 unit, and the transition from this level to the ground state is evidently[52] $M1$; thus, $I\pi$ is either $\frac{5}{2}+$

[65] R. A. Ricci, S. Monaro, and R. van Lieshout, Nucl. Phys. **16**, 339 (1960).
[66] B. Saraf, P. Harihar, and R. Jambunathan, Phys. Rev. **118**, 1289 (1960).
[67] H. W. Brandhorst, Jr., and J. W. Cobble, Phys. Rev. **125**, 1323 (1962).
[68] C. E. Gleit, C.-W. Tang, and C. D. Coryell, *Beta-decay Transition Probabilities*, supplement to Ref. 20.
[69] R. A. Golden, thesis, University of Pennsylvania, 1957; Dissertation Abstr. **17**, 1576 (1957).
[70] M. Raether, Z. Physik **150**, 38 (1958).

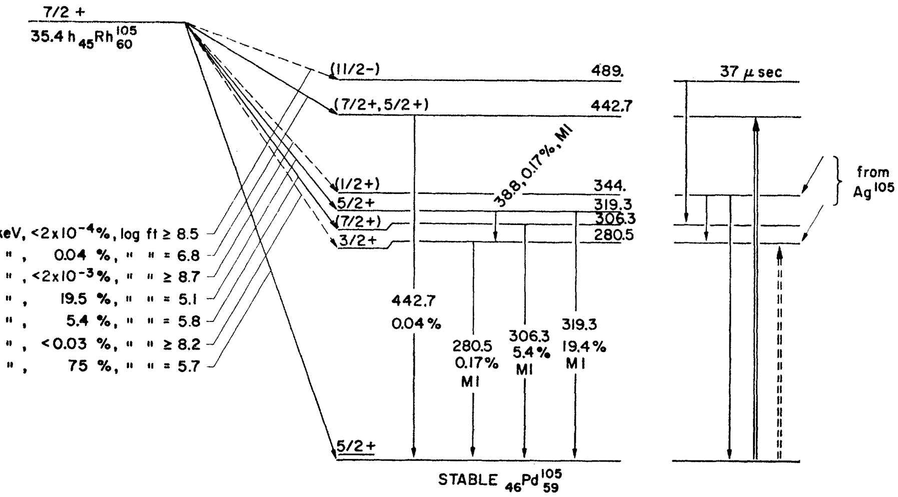

FIG. 5. Decay scheme of Rh^{105}, showing also data from other sources. There are also several Pd^{105} levels (10 or more) between 560 and 1100 keV (not shown); most of them probably have even parity. Electromagnetic transition intensities noted here *do* include internal conversion. Beta transitions indicated by dashed lines are transitions which, to within the upper limits indicated, do not occur.

or $\frac{7}{2}+$. To decide between these, we note that the transition from the 37-μsec Pd^{105} level at 489 keV seems to go only[39,40,42] to the 306-keV level. If the ground state and the 306-keV level had the same spin, then there should be from the 489-keV level not only the 183-keV transition to the 306-keV level but also a strong 489-keV transition to the ground state. Thus the 306-keV level is more likely $\frac{7}{2}+$ than $\frac{5}{2}+$. The absence ($\leq 1.5\times 10^{-3}\%$) of any 26-keV gamma is consistent with this assignment; for a $\frac{5}{2}+\rightarrow\frac{3}{2}+$ $M1$ to the 280-keV level, the expected intensity would be on the order of twice this (neglecting conversion).

The half-period and the reported[42] $M2$ nature of the 183-keV transition both indicate $\frac{3}{2}-$ or $\frac{11}{2}-$ for the 489-keV level; but $I\leq\frac{7}{2}$ is eliminated by the absence of transitions from the 489-keV level to those at 0, 280, 319, and 344 keV. Thus $\frac{11}{2}-$ is indicated for the 489-keV level, consistent with our being unable to detect any Rh^{105} beta decay to it ($\log ft\geq 8.5$).

The Pd^{105} level at 443 keV is undoubtedly the same as the one formed[34–37] with large $B(E2)\uparrow$ (electric quadrupole reduced transition probability upwards) in Coulomb excitation of Pd^{105}. Measurement of the angular correlation of the 443-keV gamma with the Coulomb-exciting beam has shown[35] that $I\pi$ is ($\frac{3}{2}$, $\frac{5}{2}$, or $\frac{7}{2}$)+. Formation of the level in beta decay of Rh^{105} eliminates $\frac{3}{2}$. Of the two remaining possibilities, $\frac{7}{2}+$ seems more likely than $\frac{5}{2}+$ because in the latter case a transition to the 280-keV ($\frac{3}{2}+$) level should have been observed as a 163–280 cascade of intensity about 10 times the observed upper limit. The beta transition to the 443-keV level (whether $\frac{7}{2}+$ or $\frac{5}{2}+$) is therefore of the allowed class, with a marked retardation ($\log ft=6.8$).

It may be that the 442.7-keV gamma transition is the same as the 443.3-keV transition reported by Suter *et al.*[42] in the decay of Ag^{105}, especially in view of their evidence that their transition has a strong $E2$ component. Their coincident 155.4-keV ($M1+E2$) transition would then imply an even-parity level at 599 keV (which they suggested as an alternative) rather than a $\frac{7}{2}-$ level at 644 keV as assumed[20,42] currently. In that case the 433 ($M1?+E2$)$-$644($E1$) cascade[42] from the 1088-keV (apparently $\frac{3}{2}-$) level implies that the 443-keV level is $\frac{5}{2}+$.

In the literature, one apparent contradiction of our results requires comment. This is the resonance fluorescence work by Metzger[41] which shows that the 319-keV Pd^{105} level is probably $\frac{7}{2}+$ rather than $\frac{5}{2}+$. He reached that conclusion in the following way: He found a mean life of $(2I+1)$ $(0.91\pm0.05)\times10^{-11}$ sec. From this and a Coulomb-excitation measurement communicated to him by P. H. Stelson [$B(E2)\uparrow=0.007$ to 0.012 e^2 b^2], he calculated that the mixing amplitude $|\delta|$ is 0.12 to 0.17 (where δ^2 is the $E2/M1$ intensity ratio for the transition). He measured the angular distribution of the resonance radiation ($A_2/A_0=0.25\pm0.03$) and noted that it cannot be fitted by any value of I_{319} within the range of $|\delta|$ above, but that a slight extension of this range (to 0.11) allows the angular distribution to be fitted if I_{319} is $\frac{7}{2}$.

However, recent measurements by Stelson[71] indicate that the lower value of $B(E2)\uparrow$ is the more nearly correct, and that $B(E2)\uparrow$ to the 306-keV level is about $\frac{1}{5}$ as much as that to the 319-keV level. The new $B(E2)\uparrow$ value thus implied for excitation of the 319-keV level is 0.006 ± 0.001 e^2 b^2. Moreover, Metzger's mean-life measurement is subject to possible effects from the presence of the 306-keV gamma, and therefore should be assigned an error of perhaps 20%. This, together with the new $B(E2)\uparrow$, then leads to $|\delta|$ values 0.10 to 0.13, consistent with $\frac{7}{2}$, but also consistent with $\frac{5}{2}$, for the 319-keV level. (With $I=\frac{5}{2}$, we calculate that the range of δ corresponding to $A_2/A_0=0.25\pm0.03$ is $0.042\leq\delta\leq0.108$.) Thus the contradiction is reconcilable.

[71] We are indebted to Dr. Stelson for making these measurements and communicating the results to us (1965, unpublished).

With this revised $|\delta|$, we infer that Metzger's mean life for the 319-keV level should be $(5\pm1)\times10^{-11}$ sec and that the $M1$ component of the 319-keV transition is some 57 times slower than predicted by the single-particle estimate. Then from our data, the 38.8-keV gamma (to the 280-keV level) is some 85 times slower than the single-particle estimate for $M1$ transitions (not taking into account a statistical factor for the spins). The $B(E2)\uparrow$ for the 319-keV transition is about twice the single-particle estimate.

One final point concerning Metzger's measurements is that they rule out the possibility of $\frac{3}{2}+$ for the 319-keV level. Since $\frac{3}{2}+$ for the 280-keV level seems reasonably well established, $\frac{7}{2}+$ for the 319-keV level is eliminated (by the 38.8-keV $M1$ transition). Thus of the original choices $(\frac{3}{2}, \frac{5}{2}, \frac{7}{2})+$, only $\frac{5}{2}+$ remains for the 319-keV level; this is the corroboration to which we alluded earlier.

NUCLEAR MODELS

Shell Model

The expected Rh^{105} proton configuration, $(2p_{1/2})^2(1g_{9/2})^5$ beyond the closure at 38, implies[72] a $\frac{9}{2}+$ ground state rather than our observed $\frac{7}{2}+$. Such anomalous $(I=j-1=\frac{7}{2})$ ground states are common in nuclei with N of 43, 45, 47, or Z of 45, 47. They are sometimes attributed to the configuration $(g_{9/2})^n$, although there is no reasonable range of nuclear forces[8,9,72] which gives $\frac{7}{2}$ as the lowest state of this configuration when n is ±3 (e.g., the Ag isotopes, where n must be -1 or -3); a similar problem occurs in ${}_{34}Se_{41}{}^{75}$ $(\frac{5}{2}+)$.

The expected order[8] of single-neutron states in Pd^{105} is $d_{5/2}$, $g_{7/2}$, $d_{3/2}$, $s_{1/2}$, $h_{11/2}$ approximately; nuclear spins and quadrupole moments in the region $51\leq N\leq63$ imply that the Pd^{105} configuration (9 neutrons beyond the closure at 50) should be $(1g_{7/2})^4(2d_{5/2})^5$. However, the observed magnetic dipole moment $(-0.6$ nm$)$[33] differs from that predicted $(-1.91$ nm$)$ by one of the widest margins known (70%). This, and the beta transition from Rh^{105}, which should be twice-forbidden ($d_{5/2}$ neutron transforming to $g_{9/2}$ proton, $\log ft\approx13$) but is merely retarded 210-fold over the estimate[9] for an allowed $g_{7/2}\rightarrow g_{9/2}$ Gamow-Teller transition (hereinafter denoted GT), would indicate $(1g_{7/2})_{5/2}{}^n$(n odd) configuration admixtures in the Pd^{105} ground state.

The Pd^{105} levels at 344 $(3s_{1/2})$, 489 $(h_{11/2})$, and 651[38] $(d_{3/2})$ keV are easily accounted for. The assignments are supported by the (d,p) and (d,t) data[38] which indicate that these levels contain the bulk of the assigned single-particle strengths.

The 319-keV level of Pd^{105} may be interpreted as the $\frac{5}{2}+$ member of the $(1g_{7/2})^3(2d_{5/2})^6$ configuration. [On the basis of known spins and quadrupole moments in the region, together with arguments like that found on pp. 69–70 of Ref. 8, $(1g_{7/2})^3(2d_{5/2})^6$ should be lower than $(1g_{7/2})^5(2d_{5/2})^4$.] This accords with the relative favoring of the beta transition to it from Rh^{105} (retarded 50-fold over GT, which is normal for l-allowed, nonmirror odd-A transitions). The transition thus behaves as one between similar states, each with anomalous $(I=j-1)$ coupling. The level cannot be $(2d_{5/2})^n$ because the beta would then be twice-forbidden; but admixtures of such type in this state, and/or $(g_{7/2})^n$ in the Pd^{105} ground state, would have to be present to some degree, for otherwise the retarded $M1$ transition to the ground state would be l-forbidden.

The 306-keV level would then be logically interpreted as the $\frac{7}{2}+$ member of the same $(1g_{7/2})^3(2d_{5/2})^6$ configuration. But then the beta transition to this level should be fast like that to the 319-keV level, whereas it is five times slower (retarded 270-fold over GT) like that to the ground state. It is not clear how this level could be described in the shell model. On this point, the (d,t) results[38] suggest that the $g_{7/2}$ single-particle strength is largely in a level at 692 keV.

The 280-keV level cannot be interpreted as the $2d_{3/2}$ single-particle level, because of evidence[38] that most of the $d_{3/2}$ single-particle strength is at 651 keV and that the single-particle amplitude of the 280-keV level is exceedingly small. Moreover, many-particle configurations like $(1g_{7/2})^n$ or $(2d_{5/2})^n$ for this level seem unlikely, since they would be expected to give higher-spin states besides, and below, the $\frac{3}{2}+$ state.

The 443-keV level has so little single-particle character that it was not observed[38] in (d,p) and barely observed in (d,t) reactions. Its $B(E2)\uparrow$ is apparently[34–37] in the range 0.1 to 0.2 e^2 b^2, or some 40 times the single-particle estimate, and the reported[35] $|\delta|$ of the 443-keV gamma is high (>0.5). The beta transition to the 443-keV level is 2700 times slower than GT; the $\log ft$ (6.8) is more characteristic of first-forbidden transitions than of allowed ones. Clearly, the level is strongly collective.

In the shell model, one explains such situations by positing a multiplet from coupling the extra neutrons to the first phonon of an even-even "core" (subject to displacements and admixings by nearby particle and other "core-plus-particle" states). Accordingly, in Pd^{105} there should be five levels $(\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \frac{7}{2}, \frac{9}{2})+$, with total $B(E2)\uparrow\sim0.6$ e^2 b^2 (as for the first 2+ state in Pd^{104} or Pd^{106}),[3,73] and with respective individual $B(E2)\uparrow$ values 0.04, 0.08, 0.12, 0.16, and 0.20 e^2 b^2; the $|\delta|$ values should be large for the reverse transitions. Beta transitions to these levels should be forbidden (although in practice[5,6,20,74,75] this is not substantiated).

N. B. Gove has suggested[20] that the five Pd^{105} levels in question may be those at 280 $(\frac{3}{2})$, 319 $(\frac{5}{2})$, 344 $(\frac{1}{2})$,

[72] D. Kurath, in *Nuclear Spectroscopy, Part B*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), Chap. VI.B.

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443 ($\frac{7}{2}$), and 785 ($\frac{9}{2}$) keV. And indeed the 443-keV level, with its large $B(E2)\uparrow$, high $|\delta|$, and retarded beta transition from Rh^{105}, could be classified as the $\frac{7}{2}$ (or $\frac{5}{2}$) member of the series. However, the three levels at 280, 319, and 344 keV do not have the required attributes. The 344-keV $B(E2)\uparrow$ is probably small since its Coulomb excitation has not been observed for certain; besides, its single-particle strength is known[38] to be large; $B(E2)\uparrow$ to the 319-keV level seems to be only about twice the single-particle estimate, as we saw; and most of the reported $B(E2)\uparrow$ values to the 280-keV level are rather small (e.g., $\sim$0.008 e^2 b^2, only four times the single-particle estimate). Moreover, the 785-keV level may[38] be $\frac{1}{2}+$ instead of $\frac{9}{2}+$, although it does reportedly[37] have a large $B(E2)\uparrow$ (0.059 e^2 b^2). Finally, the total $B(E2)\uparrow$ thus far known, to all Pd^{105} excited states, is 0.3 e^2 b^2 or less, so that some 0.3 e^2 b^2 is missing.

With pairing[76,77] (analogous to electron correlation in a superconductor) and quadrupole interactions, the calculations of Kisslinger and Sorensen[78,79] predict a Pd^{105} level scheme (see Fig. 25 of Ref. 79) for which the agreement with observation seems to be poor; also, the calculations predict $\frac{9}{2}+$ instead of $\frac{7}{2}+$ for Rh^{105}. Moreover, using the log*ft* for Rh^{105} decay in conjunction with those for Rh^{106} and Ag^{106} decay, occupation numbers $V_p^2(46g_{9/2})$ and $V_n^2(60g_{7/2})$ calculated for Pd^{105} by the method[80] of Sakai and Yoshida are respectively 0.40 and 0.51, in disagreement with values 0.06 and 0.20 obtained by those authors[80] from other sets of nuclei. Interpolating between values obtained[38] for Pd^{104} and Pd^{106} from (d,p) and (d,t) reactions, one estimates 0.6 for $V_n^2(60g_{7/2})$, which agrees better with the first set of values.

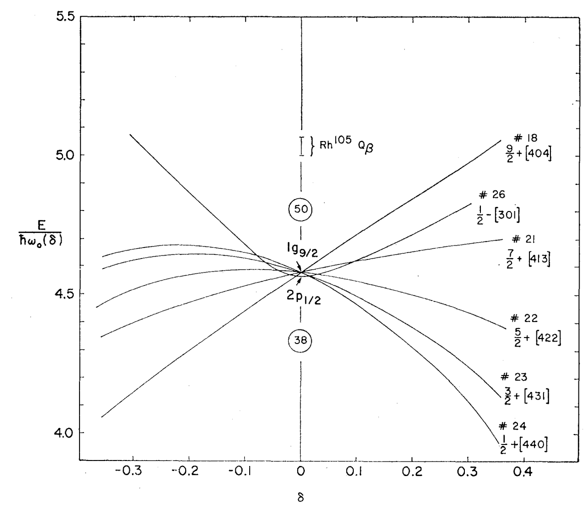

FIG. 6. Nilsson diagram for protons from $Z=38$ to $Z=50$, in δ-dependent energy units (ordinate) versus deformation (abscissa). The orbits are labeled with the numbers (No. 18, 21, 22, 23, 24, 26) corresponding to the notation of Ref. 12, and with quantum numbers $K\pi[Nn_3\Lambda]$. For $A=105$, $\hbar\omega_0(0)\simeq 8.7$ MeV. Parameters ($\mu=0.55$, $\kappa=0.0613$) and eigenvalues for protons (as distinct from neutrons) in the $N=4$ oscillator shell are from Ref. 12 [in the note (p. 19) and Table (Ib) added in proof]. The $N=3$ orbit is as ordinarily calculated (e.g., Fig. 5 of Ref. 12).

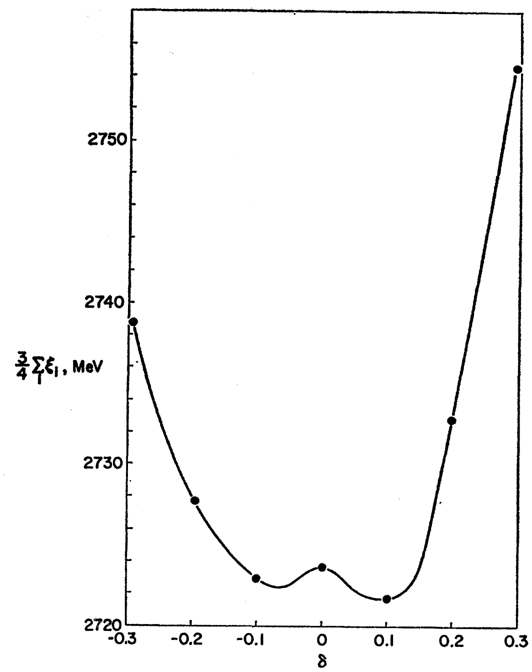

FIG. 7. Deformation dependence of total energy of Rh^{105} ground state, according to the Nilsson model. The ordinate is actually $\frac{3}{4}$ the sum of single-particle energies (see Ref. 12) rather than the total energy, which would have included Coulomb and pairing contributions (which work against each other) and a potential term which is approximately independent of deformation. In this calculation, the configuration is allowed to change as δ changes so as always to give the minimum energy for each δ. This then is an envelope curve, and *not* the energy contour for a fixed configuration versus δ.

Nilsson Model

If we modify the Nilsson calculation for protons as specified in the material added in proof to Nilsson's paper,[12] the resulting Nilsson diagram for protons in the region of interest is as shown in Fig. 6. We see that the $\frac{7}{2}+$ Rh^{105} ground state would come about naturally if the shape were prolate ($\delta>0$).[81] Figure 7 indicates that the predicted shape is indeed prolate (i.e., $\delta\sim+0.1$) for Rh^{105} (although pairing may[25,82] change this); the same is true of Pd^{105}. Lending some plausibility for such deformations is Cd^{107}, which has the same spin and neutron number as Pd^{105}; it has an electric quadrupole

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[77] A. Bohr, B. R. Mottelson, and D. Pines, Phys. Rev. **110**, 936 (1958).
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[80] M. Sakai and S. Yoshida, Nucl. Phys. **50**, 497 (1964).
[81] Here, δ denotes roughly the deformation $\Delta R/R$; earlier, δ was used to denote the $E2/M1$ mixing amplitude parameter.
[82] F. DeMichelis and F. Jachello, Nucl. Phys. **58**, 481 (1964).

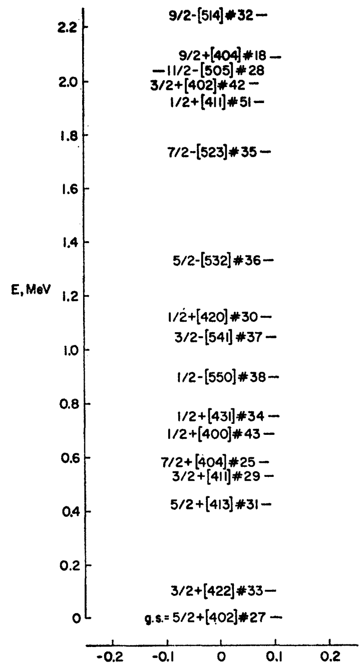

FIG. 8. Approximate δ and energy values of the first few Pd^{105} levels expected in the Nilsson model. In the calculation, the odd particle is confined to the appropriate orbital, but otherwise the calculations were carried out as described for the Rh^{105} ground state (see Fig. 7 caption). Uncertainties amount to hundreds of keV because the calculations were made only at δ intervals of 0.1 unit; these uncertainties are in addition to comparable ones inherent in the Nilsson model itself (see p. 25 of Ref. 12). The orbital numbers are those given by Nilsson (Fig. 5 of Ref. 12); there is a discrepancy between Refs. 12 and 62 in the labeling of orbitals 27, 29, 30, 31, 33, 34, 43, and 51.

moment[22] of +0.77 b, which is some seven times the shell-model estimate and corresponds to $\delta \sim +0.17$.

In contrast to the unmodified diagram,[12] Fig. 6 shows close competition between $\frac{1}{2}-$ and $\frac{7}{2}+$ levels, such as is in fact observed in the odd-A Rh and Ag isotopes, and which was a difficulty of the shell model. In general, the odd-Z nuclei of the $1g_{9/2}$ shell exhibit a turning point, $A=102$, below which the isomers are always $\frac{1}{2}-$ and $\frac{9}{2}+$, and above which they are all $\frac{1}{2}-$ and $\frac{7}{2}+$, perhaps symptomatic of the onset of deformation.

The Pd^{105} particle states expected in the Nilsson model are represented in Fig. 8. Using the known transition probabilities and the predictions of the asymptotic selection rules,[15,62,83] and keeping in mind that the level order and energy differences in the Nilsson model are only approximate (see Fig. 8 caption), the assignments to Nilsson states shown in Fig. 9 were made. The order of levels is fairly consistent with the predictions, except that the $\frac{11}{2}-$ level is predicted too high (also a problem in the shell model), and experimental evidence for level No. 33 is lacking. There are several other difficulties, to be mentioned presently (which moreover do not seem to be removed by thinking in terms of (l,j) rather than the asymptotic quantum numbers), but the assignments of Fig. 9 do succeed in fitting a fair portion of the data on beta- and gamma-transition probabilities. The hindrances of the $M1$ gammas 38.8 and 319.3 keV, and of the betas to the ground state and to the 306-keV level, are attributable to violation of asymptotic selection rules. (However, the $E2$ component of the 319.3-keV gamma should be hindered also, but is not.) The lesser retarding of the beta to the 319-keV level is consistent with general expectation[10] for transitions between particle configurations in deformed nuclei (e.g., 10 to 100 times slower than in spherical nuclei). The 443-keV level, which is taken to be the first rotational state ($\frac{7}{2}+$), is about where it should be (420 keV), if one uses an inertial parameter $\hbar^2/2J$ of 60 keV (J is the moment of inertia) as obtained from a rotational interpretation[16] of the levels of Rh^{103}, Ag^{107}, and Ag^{109}.

One of the difficulties in Fig. 9 is that no satisfactory assignment can be made to the $\frac{1}{2}+$ level at 344 keV. The 64-keV $M1$ transition from that level[42] is about 170 times weaker, relative to the 344-keV $E2$ transition from the same level, than it should be on the single-particle estimate. This favoring of the 344-keV $E2$ over the 64-keV $M1$ cannot be obtained by any permutation of the $\frac{1}{2}+$, $\frac{3}{2}+$, and $\frac{5}{2}+$ levels shown in Fig. 8 without introducing a similar problem in the relative intensities of the two transitions from the 319-keV level.

The nucleus should be oblate in the $\frac{11}{2}-$ [505] state, according to our calculations (see Fig. 8 and caption thereto); it is interesting in this sense that Cd^{113} and Cd^{115} have negative quadrupole moments in the $\frac{11}{2}-$ state[84,85] whereas Cd^{107}, Cd^{109}, and Cd^{111} have positive quadrupole moments in the $\frac{5}{2}+$ state.[21–24] However, the $M2$ transition from $\frac{11}{2}-$ [505] to the weakly prolate $\frac{7}{2}+$ [404] level, though allowed by the asymptotic selection rules, should probably be retarded by more than the observed sevenfold.

The interpretation of the 443-keV Pd^{105} level as the first rotational state ($I=\frac{7}{2}$, $K=\frac{5}{2}$) is consistent with the low cascade/crossover ratio (less than $\frac{1}{4}$ that expected if all were single-particle $M1$ transitions). The $B(E2)\uparrow$ to this rotational state[86] should be 0.22 e^2 b^2, in agreement with the most recent[37] experimental value (0.21), if we assume for Pd^{105} a quadrupole moment equal to that of Cd^{107}. But the trouble with this rotational interpretation is in the ratio of beta-transition ft values from Rh^{105} to the 443-keV and ground states; the model predicts[10,62] that $(ft)_{443}/(ft)_0$ should be 3.38, whereas our experimental value is 12.6. This difficulty is equivocal, however, because rotation-particle coupling,

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[85] M. N. McDermott, R. Novick, B. W. Perry, and E. B. Saloman, Phys. Rev. 134, B25 (1964).

[86] The formulas in Ref. 62 for $B(E2; I+1 \rightarrow I)$ and $B(E2; I+2 \rightarrow I)$ are incorrect.

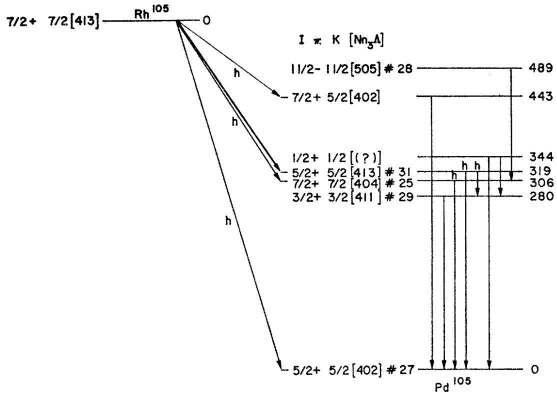

FIG. 9. Nilsson model interpretation of Rh[105] decay scheme, showing the beta and gamma transitions expected on the basis of the assignments. Beta transition intensities implied by the assignments are indicated by the heaviness of the lines. Transitions marked "*h*" are hindered by violation of asymptotic selection rules. In addition to $I\pi K[Nn_3\Lambda]$ for each level, the number designations (No. 27, 29, etc.) of Nilsson from Ref. 12 are indicated for each particle state. The Pd[105] 443-keV level is interpreted as the $I=\frac{7}{2}$ member of the $K=\frac{5}{2}$ rotational band built on the ground state, on the assumption the 443-keV level has $I=\frac{7}{2}$.

with possibly a large perturbing effect on $(ft)_{443}$, is suggested by the proximity of the 306-keV $(I=K=\frac{7}{2})$ level.

The predicted magnetic moment of the Pd[105] $\frac{5}{2}+$ [402] ground state rises steeply from -1.91 nm at $\delta=0$ to $+0.48$ nm at $\delta=+0.1$, if we use reasonable g factors $(g_R=Z/2A,\ g_S=\frac{1}{2}[g_S]_{\text{free}})$,[87,88] so that the measured moment $(-0.6\ \text{nm})$[33] is consistent with $\delta\sim+0.06$. The predictions are extremely sensitive to the $2d_{5/2}$ and $1g_{7/2}$ shell-model $(\delta=0)$ energies chosen; owing to their closeness, there is extensive mixing (which is responsible for the steep rise in the predicted moment).

The level at 280 keV in Fig. 9 is a hole state, according to the model, whereas those at 306, 319, and 489 are particle states. In principle these assignments can be tested by the (d,t) and (d,p) data.[38] The experimental situation[38] is unclear regarding the first three excited states because of the difficulty of resolving the three, but the agreement may be only fair in each case. The levels at 344 and 489 appear[38] to be particle states.

Finally, we reiterate that the $\frac{7}{2}+$ assignment for the 443-keV level, which would have to hold before the applicability of the Nilsson model can even be considered, is not established beyond doubt. Efforts to find a 280–163 cascade, which would have established $\frac{5}{2}+$ and eliminated the Nilsson model, did not succeed.

CONCLUSION

Comparison of the data with the conventional shell model and the Nilsson model leads to an ambivalent situation, suggesting a region of approaching deformation. In this connection, the critical energy of the first 2+ state for the change from vibrational to rotational spectra in even-even nuclei (Eqs. V. 7 and V. 8 of Ref. 3) is 404 keV at $A=105$—close to the first 2+ state of even-even nuclei near Pd[105]. Also, the coupling constant[3,9,36]

$$q=\left(\frac{5}{16\pi}\frac{k^2}{\hbar\omega_2 C_2}\right)^{1/2} \tag{2}$$

is about 2.9 for Pd[105] if one uses reasonable estimates[89] of $\hbar\omega_2$ and C_2. This corresponds to intermediate $(1<q<3)$ to strong $(q>4)$ coupling, i.e., incipient deformation.

Since the Nilsson model seems to fit the data about as well as the conventional shell model, and since Rh[105] and Pd[105] are in a region of supposedly spherical even-even nuclei, it might be interesting to attempt to apply the Nilsson model to neighboring nuclei (recall the earlier-cited analyses[4,10,16–19] of Rh[103], Ag[107], Ag[109], and odd-odd nuclei of this region by this model), although the prevalence of $\frac{5}{2}+$ odd-neutron ground states in this region would seem, offhand, to be a great obstacle. One might also inquire whether the odd-A and odd-odd nuclei are more amenable than the even-even ones to being treated as deformed.

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