Energy Levels of ^{100}Ru†

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The nuclear-level structure of ^{100}Ru has been investigated through study of the radioactive decay of 16-sec ^{100}Tc and 20-h ^{100}Rh. The experimental techniques employed include two-parameter Ge(Li)-Ge(Li) coincidence spectroscopy and NaI(Tl) γ-γ angular-correlation measurements. Altogether, 24 excited states of ^{100}Ru have been observed below 3.5 MeV. Examination of previous Ru(n,γ) data strongly suggests that at least seven of the observed levels are populated by primary ^{99}Ru(n,γ) transitions. The present results, combined with previous internal-conversion and angular-correlation data, yield unique spin-parity assignments for nine levels, four of which are 0^+ (at 1130.4, 1740.6, 2051.5, and 2387 keV). Also, through selection-rule arguments, narrow limits have been placed on the spin-parity values for the remaining states, almost all of which are of low spin (≤ 2). The assignments deduced for the parent nuclei are 1^+ for ^{100}Tc and 1^- for ^{100}Rh. The β branching of ^{100}Tc is found to be anomalous in that the transitions to the lowest two 2^+ levels are extremely hindered compared to those that proceed to the lowest two 0^+ levels.

I. INTRODUCTION

The present investigation of the level structure of ^{100}Ru was prompted to a large extent by the following considerations: (1) Both 16-sec ^{100}Tc and 20-h ^{100}Rh are known to have unusually large β-disintegration energies (3.4 and 3.6 MeV, respectively), suggesting that high-resolution spectroscopic studies of their radiations should reveal a wealth of information about the level structure of their common daughter ^{100}Ru up to a rather high excitation energy. (2) Earlier work[1] at this laboratory by two of the present authors suggested that several 0^+ levels of ^{100}Ru are populated in the ^{100}Tc decay, and it appeared desirable to obtain further verification of these results, particularly since the location and behavior of the first few 0^+ states constitute a basic test of possible nuclear coupling schemes for an even-even nucleus.

Previous studies of ^{100}Rh, notably by Kawakami and Hisatake[2] and by Koike *et al.*,[3] had shown that this decay scheme is quite complex. In our investigation, with the help of a Ge(Li)-Ge(Li) coincidence spectrometer, it has been established that a total of 23 energy levels of ^{100}Ru are populated in this decay. Ten of these states are also populated in the ^{100}Tc decay; in addition, ^{100}Tc populates two levels that are not observed in the ^{100}Rh decay. From a combination of our data and the results of the earlier angular-correlation[2,3] and conversion-electron[3] measurements, unique spin-parity assignments for a number of the observed ^{100}Ru levels can be made. Unique assignments are also indicated for the two parent states.

Following the completion of our experimental work, the results of a Ge(Li) study of the ^{100}Rh decay, performed at the Leningrad State University, were published.[4] All but one of the 12 excited states they propose are confirmed by the present measurements.

II. SOURCE PREPARATION

The 16-sec ^{100}Tc sources were produced by irradiating samples of ^{99}Tc in the form of technetium oxide[5] with thermal neutrons. A few mg of the material were sealed into individual polyethylene capsules for irradiation and counting. The irradiation times ranged from 0.25 to 1.5 min, depending on the type of experiment. For singles counting the samples were bombarded for $\approx$40 sec in a neutron flux of $\approx 3\times10^{11}$ n/cm^2 sec. To obtain the spectrum of background events from longer-lived activities (see Sec. III A), the bombarding times were increased to 1.5 min. In sample bombardments for the coincidence experiments (Secs. III B and III C) the flux was reduced to $\approx 1\times10^{10}$ n/cm^2 sec, and the irradiation times were decreased to 10–20 sec. The counting of each source was begun $\approx$6 sec after the end of irradiation.

The 20-h ^{100}Rh activity was obtained from the ^{100}Ru(p,n)^{100}Rh reaction. Isotopically enriched ($\geq$97.5% ^{100}Ru) ruthenium metal[5] targets were bombarded with 9-MeV protons at the LASL cyclotron. Each target ($\approx$15 mg) was bombarded with an average proton current of 25 μA for about 6 h. Prior to counting, the sources were allowed to age for about 5 h to reduce the contribution to the data from trace amounts of 4.7-h ^{99m}Rh. The presence of 4.5-day ^{101m}Rh did not become noticeable until $\approx$48 h after bombardment.

III. EXPERIMENTAL PROCEDURE

A. Singles Data

Singles spectra were obtained with 2.5-cm^3 and 45-cm^3 Ge(Li) detectors having resolutions [full width at

† Work supported by the U. S. Atomic Energy Commission.
[1] M. E. Bunker and J. W. Starner, Bull. Am. Phys. Soc. **7**, 342 (1962).
[2] H. Kawakami and K. Hisatake, J. Phys. Soc. Japan **24**, 614 (1968).
[3] M. Koike, K. Hisatake, N. Ono, and K. Takahashi, Nucl. Phys. **54**, 129 (1964).
[4] N. M. Anton'eva, E. P. Grigoriev, G. S. Katykhin, L. F. Protasova, J. Breal, J. Liptak, and J. Urbanec, Izv. Akad. Nauk SSSR, Ser. Fiz. **33**, 27 (1969).
[5] Obtained from Isotopes Division, Oak Ridge National Laboratory, Oak Ridge, Tenn.

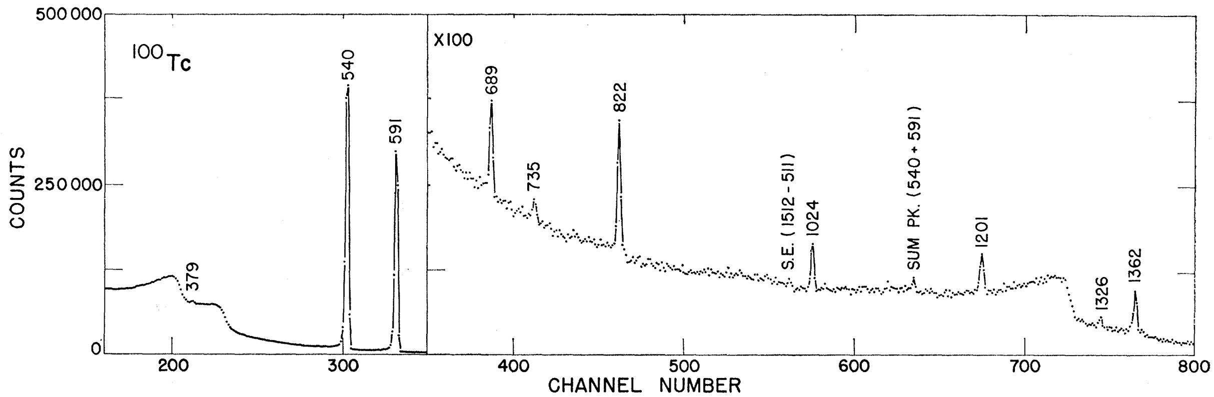

FIG. 1. Low-energy singles spectrum of γ rays observed in the decay of 16-sec ^{100}Tc. The data were recorded with a 2.5-cm^3 Ge(Li) detector.

half-maximum (FWHM) at 662 keV] of about 2.0 and 2.6 keV, respectively. The low-energy spectra (0–1500 keV) were recorded with the smaller detector, used in conjunction with a room-temperature FET preamplifier, a linear amplifier employing pole-zero compensation, and a 1600-channel analyzer. The larger detector was used to obtain the high-energy (1200–3700 keV) part of the singles spectra. A biased amplifier was used in collecting the high-energy data.

The ^{100}Tc singles data are displayed in Figs. 1 and 2. Each spectrum is the result of summing the individual spectra obtained from a succession of 150 sources. In order to enhance the relative counting rate of the high-energy γ rays in the spectrum shown in Fig. 2, a 1-cm Pb absorber backed with Cd was placed in front of the detector. This served two purposes. First, much more intense sources could be used in order to obtain improved statistics in the high-energy region without jeopardizing the system resolution. Secondly, sum peaks due to cascades involving the 540- and 591-keV transitions were virtually eliminated. Each source was irradiated for $\approx$40 sec and counted for 1 min. As the ^{100}Tc decayed during the counting interval, the source-to-detector distance was decreased every few seconds to maintain a constant counting rate of $\approx$4000 counts/sec.

In order to identify any lines in the above spectra arising from possible contaminant activities in the

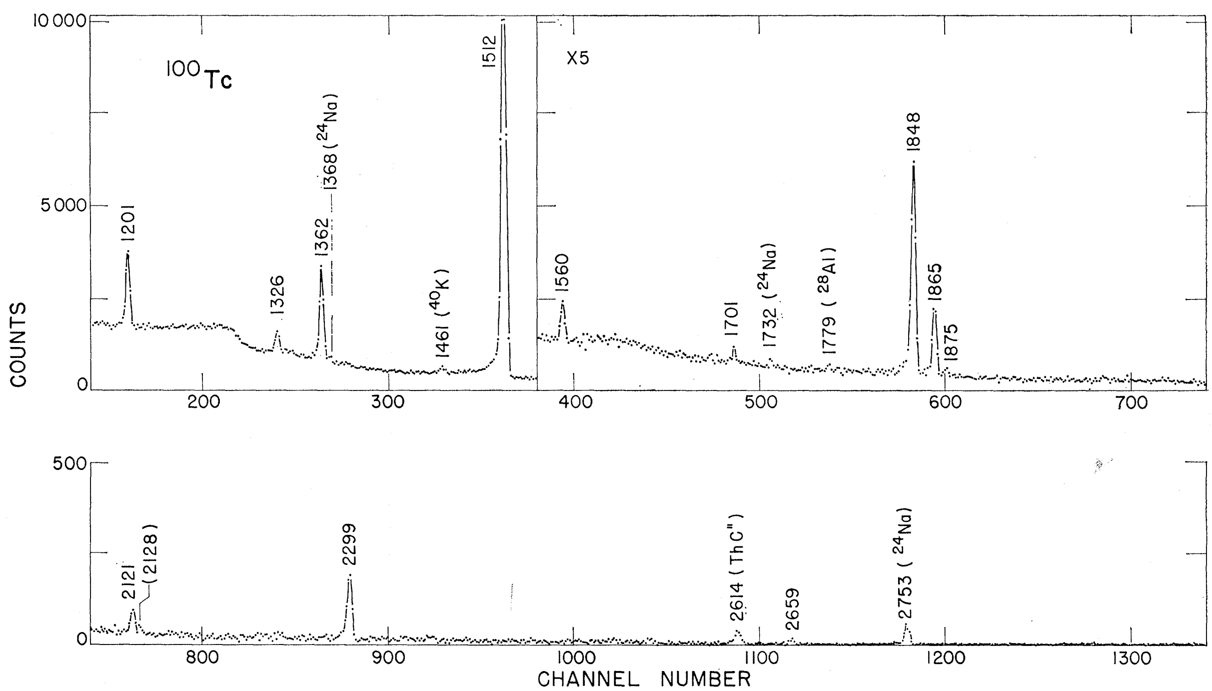

FIG. 2. High-energy singles spectrum of γ rays observed in the decay of ^{100}Tc. The data were recorded with a 45-cm^3 Ge(Li) detector. A 1-cm Pb–1-mm Cd absorber was placed between the source and the detector.

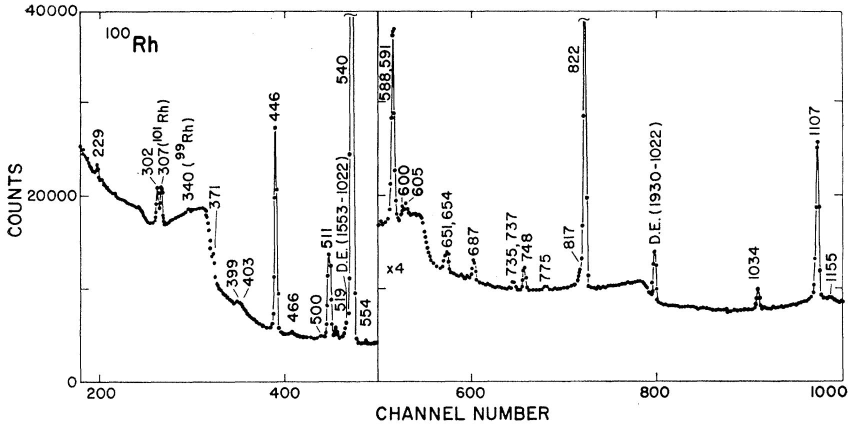

FIG. 3. Low-energy singles spectrum of γ rays observed in the decay of 20-h ^{100}Rh. The data were recorded with a 2.5-cm^3 Ge(Li) detector.

source, the counting was repeated under the following altered conditions. The samples were bombarded for 1.5 min to saturate the 16-sec ^{100}Tc activity and thus enhance any longer-lived background activity. Also, the start of the 1-min counting interval for each source was further delayed by 30 sec to change the background-to-^{100}Tc ratio. Under these conditions, the relative contribution to the spectra from a hypothetical longer-lived contaminant having a half-life as short as 30 sec is approximately doubled, while the increase is a factor of 10 for activities of infinite half-life. On the other hand, the relative contribution to the background spectrum from a hypothetical 10-sec activity is decreased by a factor of 3. The only contaminant γ rays observed in this manner were identified as arising from ^{24}Na and ^{28}Al. Room-background lines due to ^{40}K and ThC'' were also observed.

The low- and high-energy ^{100}Rh singles data are displayed in Figs. 3 and 4, respectively. The indicated sum peaks were identified by comparing singles spectra obtained at greatly different solid angles. In order to identify any possible longer-lived-contaminant activities present in the source, background spectra were recorded at $\approx$100 h after bombardment and again at $\approx$160 h. A trace of 4.7-day ^{101m}Rh activity was observed in these spectra.

The energies and relative intensities of the γ rays observed in this study are listed in Tables I and II. The energy values of the prominent ^{100}Rh lines were obtained by counting ^{100}Rh sources simultaneously with various sets of calibration sources. With the aid of a biased amplifier, four regions of the spectrum were expanded to dispersions ranging 0.31–1.16 keV/channel. Second- and third-degree polynomial calibration curves were obtained from the energies and centroids of the standard lines, and these were used to determine the energies of the stronger ^{100}Rh γ rays. The latter became the reference points for measuring the energies of the weaker γ rays in subsequent spectra.

In the case of the ^{100}Tc decay, it was feasible to measure only the 540- and 591-keV transition energies

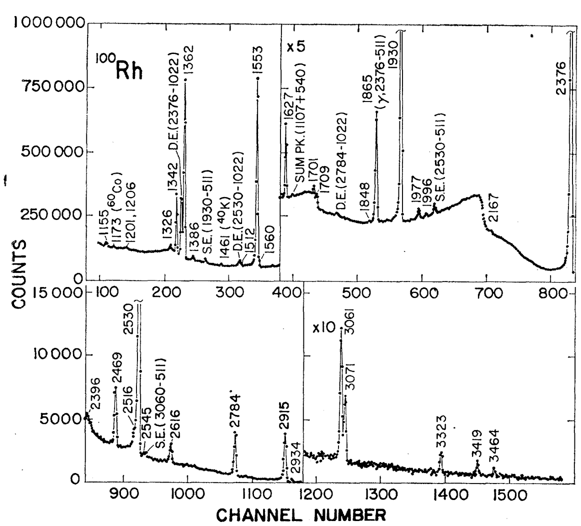

FIG. 4. High-energy singles spectrum of γ rays observed in the decay of ^{100}Rh. The data were recorded with a 45-cm^3 Ge(Li) detector.

TABLE I. Energies and relative intensities of γ rays observed in the decay of ^{100}Tc.

Energy (keV)	Relative intensity[a]
378.6±0.5	0.42±0.1
539.59±0.05	100
590.83±0.05	82±6
689.4±0.3	0.48±0.1
734.7±0.5	0.14±0.05
822.5±0.3	0.97±0.2
1024.5±0.5	0.48±0.1
1201.1±1.0	0.61±0.1
1325.7±0.5	0.15±0.05
1320.1±0.5	0.86±0.1
1512.2±0.3	6.3±0.6
1559.7±0.5	0.10±0.05
1701.0±1.0	0.02±0.01
1847.7±0.3	0.58±0.1
1865.2±0.5	0.19±0.05
1875.0±1.0[b]	0.02±0.01
2121.2±0.7	0.05±0.01
2127.7±1.0[b]	0.02±0.01
2298.6±0.5	0.20±0.05
2659.5±1.0	0.02±0.01

[a] γ intensity only.
[b] Not placed in decay scheme.

TABLE II. Energies and relative intensities of γ rays observed in the decay of ^{100}Rh.

Energy (keV)	Relative intensity[a]	Energy (keV)	Relative intensity[a]
229.1±0.3	0.5±0.1	1325.7±0.3	1.5±0.2
301.8±0.3	0.4±0.2	1341.6±0.2	23.5±1.0
302.3±0.3	3.2±0.4	1362.1±0.1	73±2.0
370.6±0.3	2.0±1.0	1386.5±0.3	1.9±0.2
398.7±0.3	0.7±0.2	1512.2±0.5	0.6±0.3
403.5±0.3	0.9±0.2	1553.4±0.2	100
446.2±0.1	54.5±2.0	1559.7±1.0	3.0±1.0
465.8±0.3	0.5±0.2	1627.5±0.3	7.7±0.5
499.8±0.3	0.7±0.2	1701.0±0.4	1.1±0.1
519.1±0.2	3.5±0.7	1709.0±0.5	1.1±0.1
539.6±0.1	381±10	1847.7±0.3	0.2±0.1
553.6±0.3	0.4±0.2	1865.2±0.5	1.9±0.5
588.2±0.2	20±1	1929.7±0.2	59±2
590.8±0.1	7.0±1.0	1976.8±0.4	1.5±0.2
599.9±0.4	1.3±0.2	1996.4±0.4[c]	0.2±0.1
604.9±0.3	1.8±0.3	2167.0±1.0	0.9±0.3
650.9±0.5	2.5±0.5	2194.0±1.0	0.6±0.3
654.5±0.5	2.2±0.5	2376.1±0.3	170±12
686.9±0.3	3.2±0.3	2395.7±1.0	0.5±0.3
689.4±1.0[b]	0.06±0.06	2469.4±0.4	0.9±0.5
734.7±1.0	1.2±0.5	2516.0±1.0	0.3±0.2
736.9±1.0	0.5±0.3	2530.2±0.2	13±3
748.5±0.2	4.0±0.2	2545.0±1.0[c]	0.1±0.05
775.5±0.6	0.4±0.2	2616.3±0.3	0.5±0.2
817.0±1.0	3±2	2784.5±0.4	1.2±0.2
822.5±0.2	98±5	2915.5±0.3	0.2±0.2
903.0±1.0[b]	0.6±0.2	2934.3±0.5	0.06±0.03
1034.3±0.3	7.0±0.3	3060.6±1.0	0.4±0.1
1107.1±0.2	64.5±2.0	3071.0±1.0	0.2±0.1
1155.1±0.5	0.7±0.3	3323.4±1.0	0.06±0.02
1201.1±1.0	0.3±0.2	3419.0±1.5	0.04±0.02
1206.0±1.0	0.2±0.1	3464.0±1.5	0.02±0.01

[a] γ intensity only.
[b] Observed in coincidence data only.
[c] Not placed in decay scheme.

with the internal calibration technique. The energies of the other γ rays were determined by referring to calibration spectra recorded immediately before and after the singles data. The set of calibration sources used in this study consisted of ^{198}Au, ^{22}Na, ^{137}Cs, ^{54}Mn, ^{88}Y, ^{60}Co, ^{24}Na, and ThC''.

TABLE III. γ-γ coincidence relationships observed in the decay of ^{100}Tc.

Gating transitions (keV)	Coincident γ rays (keV)
540	379,[a] 591, 690,[a] 822, 1024, 1201, 1326, 1512, 1848, 2299[a]
591	540, 735
690	540, 822, 1362
822	248,[b] 379, 540, 690, 1024
1024	540, 1362
1201	540
1362	379,[a] 690,[a] 1024[a]
1512	540
1848	540
All γ rays[c]	379, 540, 591, 690, 735, 822, 1024, 1201, 1326, 1362, 1512, 1848, 2121, 2299
All γ's >591 keV	379, 540, 591, 690, 822, 1024, 1362

[a] Presence in spectrum suggested but not statistically conclusive.
[b] Neither observed in singles data nor accommodated by proposed level scheme. Apparent presence in spectrum may be a statistical effect.
[c] Integral gate.

The relative intensities of the γ rays were determined by correcting the peak areas for detector efficiency. The relative efficiency curve for each detector was based on measurements made on a set of standard calibration sources.[6] An empirical escape-peak efficiency curve was used as an aid to identifying annihilation-radiation escape peaks of high-energy γ rays. By comparing the prediction of this latter curve with the observed escape-peak–photopeak ratio for each suspected escape peak, it was possible to establish whether all or only a part of the peak at energy $E_\gamma - 1022$ keV or $E_\gamma - 511$ keV was due to the pair-production process.

A search was made with a high-resolution Si(Li) detector (0.5 keV FWHM at 60 keV) for possible γ rays in the energy range 10–200 keV. No such transitions were observed in the decay of either ^{100}Tc or ^{100}Rh.

The half-life of ^{100}Tc was measured using the multiscale technique. The gross γ-ray counting rate was recorded every 0.8 sec over a five-half-life interval. A least-squares fit to the decay curve yielded $T_{1/2} = 15.8 \pm 0.1$ sec.

[6] Obtained from International Atomic Energy Agency, Vienna.

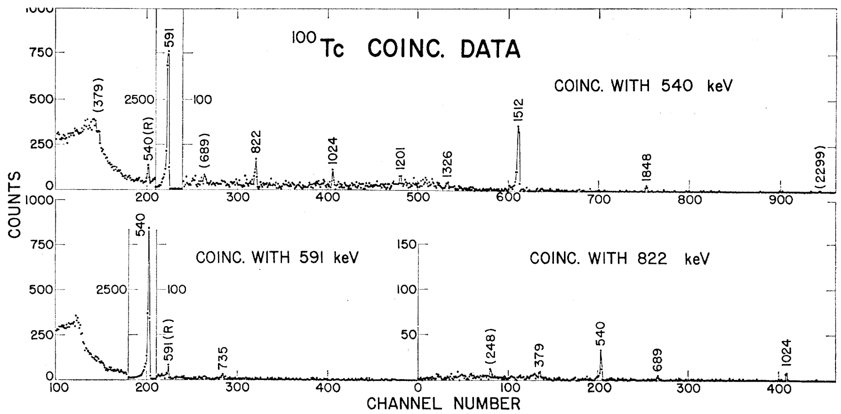

FIG 5. Selected γ-γ coincidence spectra observed in the decay of ^{100}Tc. These spectra (and those in Figs. 6 and 7) were recorded with a two-parameter Ge(Li)-Ge(Li) coincidence system. Peaks labeled (R) are due to random events.

B. Coincidence Experiments

Coincidence relationships among the γ rays emitted in the decays of ^{100}Tc and ^{100}Rh were studied with a Ge(Li)-Ge(Li) coincidence spectrometer. The two detectors employed had active volumes of 30 cm^3 and 45 cm^3 and resolutions (FWHM at 662 keV) of about 2.9 and 2.6 keV, respectively. The coincidence events, analysed in a two-parameter mode with a pair of 1600-channel analog-to-digital converters, were recorded on magnetic tape. The coincidence circuit was of conventional type, employing crossover timing. The resolving time (2τ) was $\approx$200 nsec. The detectors were oriented at 180° in order to achieve minimum separation and hence maximum coincidence efficiency. A slotted Pb-Cd absorber was placed between them to reduce the contribution to the data from crystal-to-crystal scattering. The sources were positioned in the slot so that there was no absorber (other than 0.6 cm of Be used to stop β rays) directly between the source and either detector.

In the ^{100}Tc coincidence experiment, it was necessary to integrate the data from numerous short runs. Eighty source samples were cycled through repeated irradiations over a 3-day period, for a total of 1000 irradiations. Each sample was irradiated for $\approx$15 sec and counted for $\approx$30 sec. At the beginning of each 30-sec counting interval the singles rate in the larger of the two detectors was $\approx$4500 counts/sec. With this source strength, the initial ratio of true to random coincidence events was $\approx$5:1.

The ^{100}Rh coincidence experiment yielded a total of 14 million events in a 90-h period. The source strength was increased every 10 h to maintain the singles counting rate at $\approx$3000 counts/sec in the larger Ge(Li) detector. With this source strength, the true-to-random ratio was $\approx$30:1.

A summary of the principal coincidence relationships

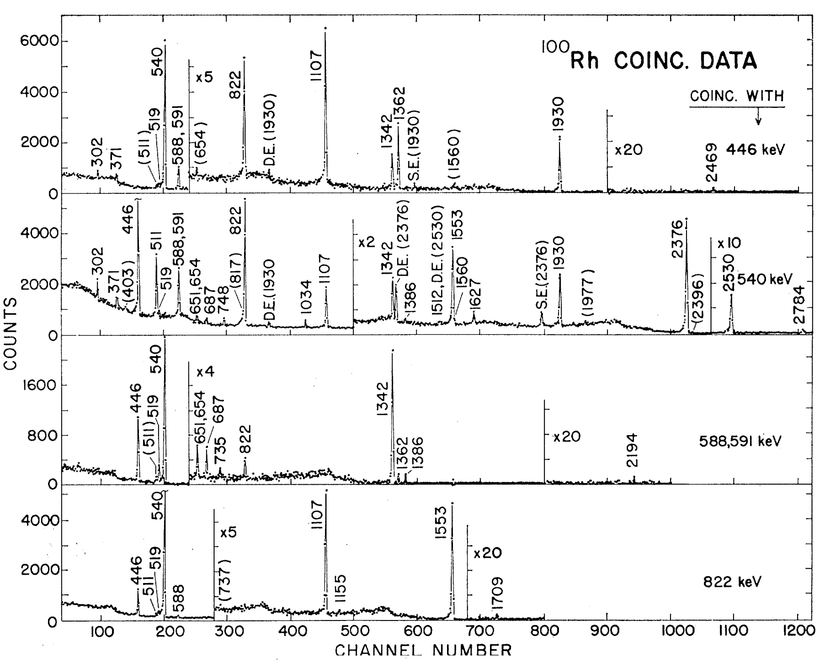

FIG. 6. Selected γ-γ coincidence spectra observed in the decay of ^{100}Rh.

TABLE IV. γ-γ coincidence relationships observed in decay of ^{100}Rh.

Gating transition (keV)	Coincident γ rays (keV) Definite[a]	Possible[b]
229	446, 540	588, 822, 1701
302[c]	302,[c] 446, 540, 591, 735, 748 1627, 1865	1326
371	446, 540, 822, 1560	511, 737, 1107
446	302, 371, 540, 588,[c] 822, 1107, 1342, 1362, 1930, 2469	511, 519, 654, 1560
466	540, 1512	689
540	302, 371, 446, 511, 519, 588,[c] 653,[c] 687, 748, 822, 1034, 1107, 1342, 1386, 1553, 1560, 1627, 1930, 2376, 2530, 2784	403, 817, 1326, 1512, 1701, 1977, 2396
588, 591	446, 511, 519, 540, 653,[c] 687, 735, 822, 1342, 1362, 1386, 2194	
600	1107, 1930	
605	1326, 1865	446, 591, 735, 1107
651, 654	446, 540, 588,[c] 687, 735, 1034	756[d]
687	540, 588, 654	
735, 737	302, 371, 540, 591, 651	822
748	302, 540, 1627	1078,[d] 1114,[d] 1362
817		1560
822	446, 519, 540, 588, 1107, 1155, 1553, 1709	511, 737
1034	519, 540, 654, 687, 1342	
1107	446, 540, 822, 1362	
1342	446, 540, 588, 1034	1553
1560	371, 446, 540, 817	
1627	302, 446, 540, 748, 903	822
1865[c]	511, 540, 605, 651	302, 1206

[a] Present in coincidence spectrum with intensity consistent with singles data and proposed decay scheme.
[b] Presence in coincidence spectrum not conclusive.
[c] Doublet.
[d] Neither observed in singles data nor accommodated by proposed level scheme. Apparent presence in spectrum may be a statistical effect.

deduced in the present experiments is given in Tables III and IV. To avoid unnecessary duplication, several moderately strong transitions are not listed as coincidence gates. For example, in Table IV it is not necessary to list the transitions in coincidence with both the 1362- and 822-keV γ rays since it is well established by a number of coincidence spectra that these two transitions depopulate the same state. Portions of the ^{100}Tc and ^{100}Rh coincidence data are displayed in Figs. 5–7. All of the ^{100}Tc cascades reported earlier[1] on the basis of scintillation studies are confirmed by our data; in addition, four new cascades have been established. In the case of ^{100}Rh, a large fraction of the coincidence relationships listed in Table IV had not been observed previously.

In the ^{100}Tc decay, normalization of β-ray intensities to a percentage scale was accomplished through a standard β-γ coincidence measurement of the direct β feeding of the 1130-keV level. The β detector used was a plastic scintillator, and the γ detector was a NaI(Tl) crystal. The primary measurement consisted of determining the number of (β, 591-keV γ) coincidences per emitted β particle, using a counting geometry in which the γ-ray efficiency of the NaI(Tl) detector was well known. Since the γ-ray data clearly indicate that the β transition to the 1130-keV level is much stronger than that to any other excited state, corrections to the observed $N_{\beta\gamma}/N_\beta$ value for the indirect β feeding of the 1130-keV state were quite small. The final value obtained for the β-branch intensity to the 1130-keV level was 5.7%. This value, used in combination with the observed γ-ray relative intensities and the deduced γ-ray intensity imbalance at each excited state, establishes the percentage β branching to the other levels.

C. Angular-Correlation Studies

In the ^{100}Tc→^{100}Ru decay, γ-γ angular-correlation measurements were made on several cascades involving the 540-keV ground-state transition and selected transitions that feed the 540-keV level. The object of these experiments was to determine, for each cascade, the correlation function $W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$, where θ is the angle of emission between two successive radiations. The measurements were performed with NaI(Tl) detectors. In spite of the rather poor resolution, the scintillator data could be interpreted unambiguously since the Ge(Li)-Ge(Li) data clearly indicated that the NaI(Tl) peaks of interest were essentially "uncontaminated" by contributions from other cascades. As in all other ^{100}Tc experiments, it was necessary to sum the data from a series of runs. In each run, at fixed angle θ, the primary datum consisted of the integrated number of coincidence counts in the photopeak of interest,

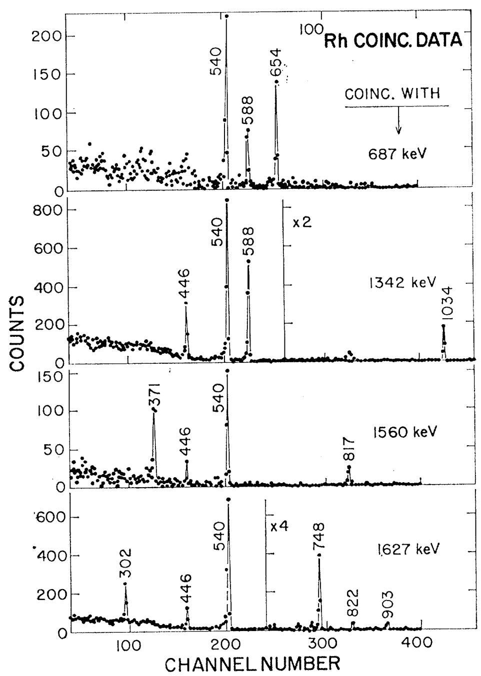

FIG. 7. Selected γ-γ coincidence spectra observed in the decay of ^{100}Rh.

divided by the net integrated singles count in one of the detectors.

In the case of the intense 591-540-keV cascade, 5.1×5.1-cm crystals were used. To suppress crystal-to-crystal scattering, a cylindrical Pb shield with an entrance window in the shape of a truncated cone was placed around each detector, in an arrangement similar to that shown in Ref. 7. The sources were mounted coplanar with the detector axes, each source-crystal distance being 7.3 cm. The gating region for both detectors was set to span the composite 591-540-keV photopeak. The fact that both γ rays were detected in each coincidence channel doubled the coincidence counting efficiency, with the result that only 25 samples were required to obtain the results shown in Fig. 8.

The 822-540-, 1201-540-, 1512-540-, and 1848-540-keV correlations were measured simultaneously, using the same setup as described above except that the two NaI(Tl) detectors were 7.6×7.6 cm, the source-to-detector distances each being 9.3 cm. The energy window for the movable-detector coincidence channel extended from 0.5 to 2.0 MeV, while that for the fixed detector spanned only the 540-keV photopeak. Data were recorded successively at 90°, 130°, 150°, and 180°, the angle between the detector axes being changed after every nine samples. The final data correspond to the accumulated results from a total of 450 sources.

The measured correlation functions $W(\theta)$ for the five cascades mentioned above are shown in Figs. 8–10. The curves represent least-squares fits to the experimental data points. The values indicated for the coefficients A_2 and A_4 for each set of data include detector solid-angle corrections. A comparison is made in Fig. 11 between the experimental and theoretical A_2, A_4 values. The theoretical A_2, A_4 value for a 0-2-0 cascade so nearly coincides with the experimental value for the 591-540-keV correlation that the two points are shown as degenerate in Fig. 11. It is evident from the figure that the 591-, 1201-, 1512-, and 1848-keV γ rays each depopulate a 0^+ state in ^{100}Ru. The measured angular-correlation function for the 822-540-keV cascade is consistent only with a 2(1, 2)2(2)0 correlation, the 822-keV transition being predominantly $E2$. Our result ($A_2=-0.16\pm0.11$, $A_4=0.47\pm0.19$) is in good agreement with the most recent angular-correlation result[2] ($A_2=-0.196\pm0.024$, $A_4=0.324\pm0.030$) obtained for the 822-540-keV cascade observed in the decay of ^{100}Rh.

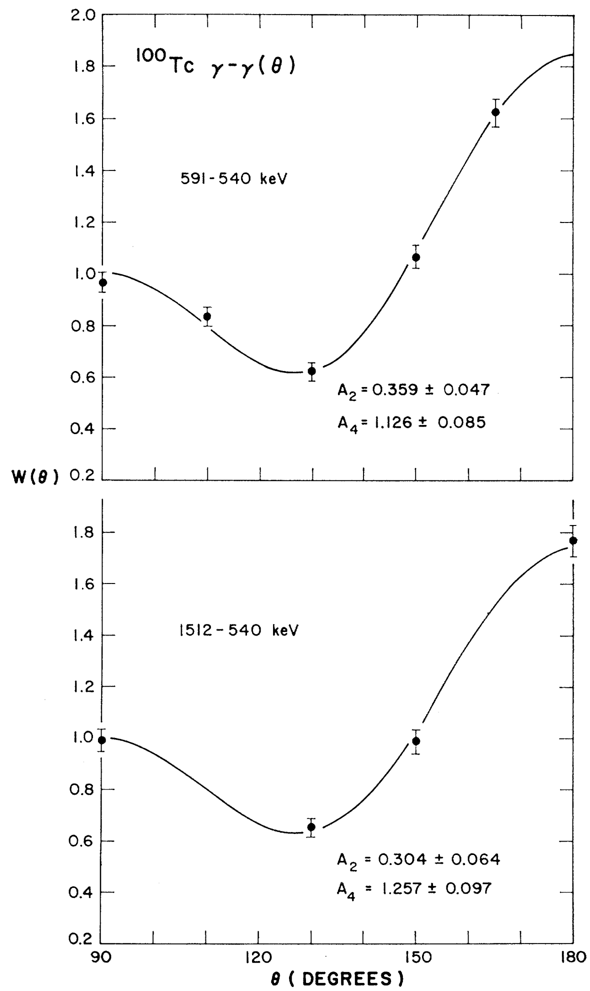

FIG. 8. Results of angular-correlation measurements of γ-γ cascades emitted in the decay of ^{100}Tc. The curve represents a least-squares fit to the data points. The indicated uncertainties in the values for A_2 and A_4 are based on the statistical errors of the individual data points.

[7] M. E. Bunker, J. P. Mize, and J. W. Starner, Phys. Rev. 105, 227 (1957).

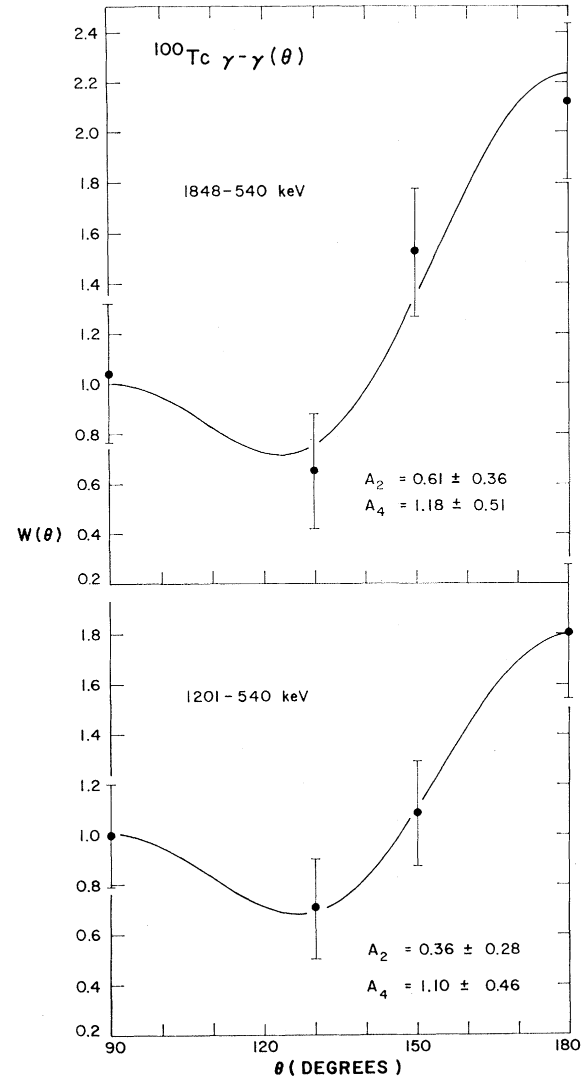

FIG. 9. See caption for Fig. 8.

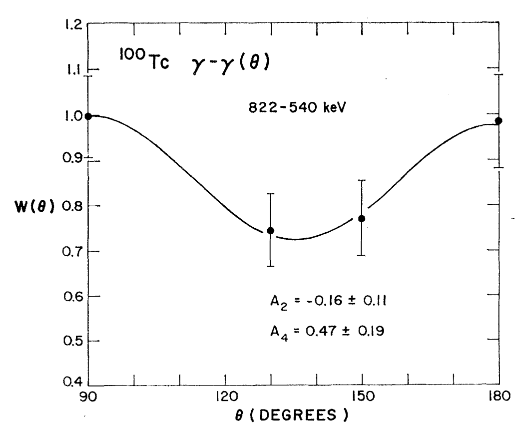

FIG. 10. See caption for Fig. 8.

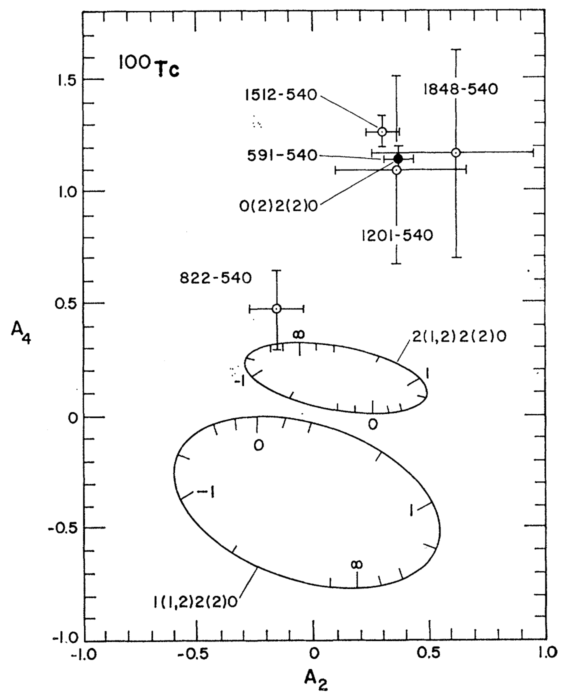

FIG. 11. Comparison of measured A_2, A_4 values with theoretical values for 0(2)2(2)0, 2(1, 2)2(2)0, and 1(1, 2)2(2)0 cascades. The theoretical locus for the 0(2)2(2)0 cascade (black dot) coincides with the measured value for the 591–540-keV cascade. The theoretical loci for 3(1, 2)2(2)0 and 4(2)2(2)0 cascades involve A_2 values ≤ 0 and for simplicity are not included in the figure.

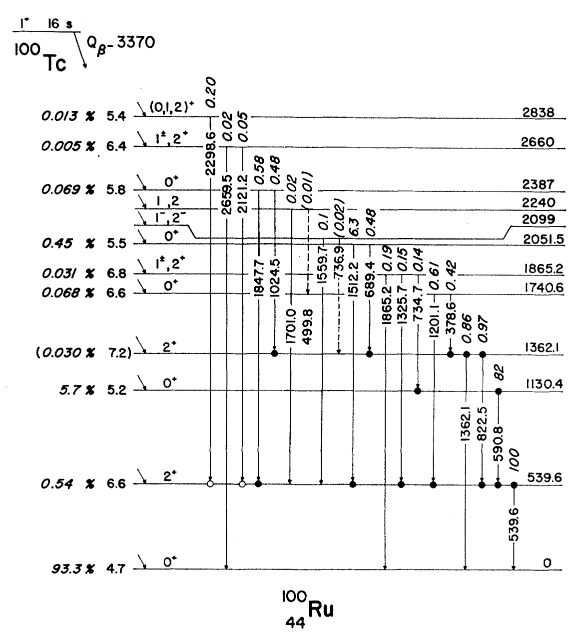

FIG. 12. Proposed decay scheme of ^{100}Tc. A closed circle at the head (tail) of an arrow indicates that a coincidence relationship was observed between that transition and one or more γ rays which follow (precede) it in the level scheme. Open circles indicate "probable" coincidence relationships. The transitions shown by dashed lines were unobserved but are assumed to exist in view of the proposed decay scheme for ^{100}Rh.

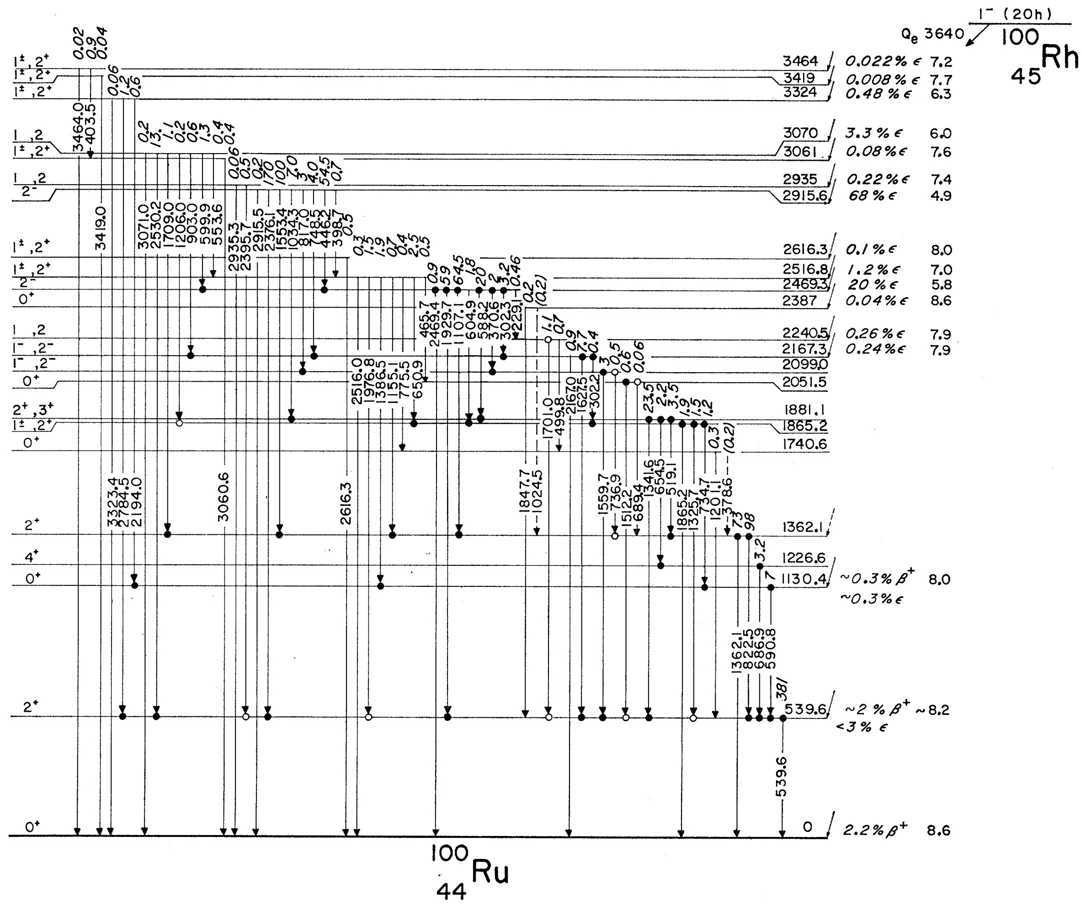

FIG. 13. Proposed decay scheme of ^{100}Rh. Meaning of coincidence dots is given in caption for Fig. 12. The logft values for the β^+ transitions to the 0- and 540-keV states are taken from Ref. 10.

IV. PROPOSED DECAY SCHEMES

The decay schemes of 17-sec ^{100}Tc and 20-h ^{100}Rh deduced from our studies are shown in Figs. 12 and 13, respectively. The former contains 11 excited states and accommodates 18 of the 20 observed ^{100}Tc γ rays. The latter involves 22 levels and 64 of the 66 observed γ transitions. The coincidence relationships among the γ rays (Tables III and IV) are indicated in both figures (see caption for Fig. 12). In Fig. 14, we present a summary of all of our observed ^{100}Ru levels and show which of these are also populated in Coulomb excitation[8] and/or the (n, γ) reaction.[9]

The *relative* β transition and/or electron-capture transition intensities to the various excited levels in ^{100}Ru were determined by considering the total γ-intensity imbalance at each level. We have described earlier (Sec. III-B) how the relative β^--group intensity values for the ^{100}Tc decay were converted to a percentage scale. In the case of the ^{100}Rh decay branches, normalization to a percentage scale is more straightforward since only a small fraction of the total decay proceeds to the ground state. All of the intensities shown in Fig. 13 are from our work with the exception of those for the β^+ branches to the ground and first excited states, which are taken from Marquez.[10] We note that Anton'eva *et al.*[4] report somewhat stronger ($\approx$4%) β^+ feeding of the 540-keV level; however, our calculated branching intensities to the higher-energy levels are insensitive to which of these values is adopted. The logft values shown in Figs. 12 and 13 were obtained with the aid of the Moszkowski nomogram.[11]

Brief descriptions of how the ^{100}Tc and ^{100}Rh schemes were constructed are given below.

A. ^{100}Tc

States are established at 539.6 and 1130.4 keV by the intense 591-540-keV γ-ray cascade. Placement of

[8] F. K. McGowan, R. L. Robinson, P. H. Stelson, and W. T. Milner, Nucl. Phys. **A113**, 529 (1968).

[9] N. C. Rasmussen, V. J. Orphan, Y. Hukai, and T. Inouye, quoted by G. A. Bartholomew *et al.*, Nucl. Data, Sec. A **3**, 609 (1967).

[10] L. Marquez, Phys. Rev. **92**, 1511 (1953).

[11] C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1967).

the intermediate state at 540 keV is clearly indicated by the large number of other γ rays observed in coincidence with 540-keV photons but not with those of energy 591 keV.

The 540-keV transition was also observed to be coincident with 822-, 1201-, 1325-, 1512-, and 1848-keV γ rays. Since none of these five γ rays was found to be coincident with any other members of this set, states are implied at 1362, 1741, 1865, 2051, and 2387 keV, respectively. The 1362- and 1865-keV γ rays observed in singles data are assumed to be ground-state transitions from levels of these energies. The observed coincidences between the 822-keV and the 379-, 689-, and 1024-keV γ rays suggest that the 1741-, 2051-, and 2387-keV levels also decay to the 1362-keV state. This was confirmed by examination of the spectrum coincident with the 1362-keV transition. The 1865-keV level was also shown to decay to the 1130-keV state via the 735-keV transition.

Peaks at 2121 and 2299 keV were present in the integral coincidence spectrum, but because of the small total number of counts, it was not possible to show conclusively what coincidence relationships were responsible for these peaks. Since we found no unexplained low-energy γ rays, consistent with our assumption that states above 2 MeV are not apt to be fed significantly by low-energy γ transitions, we propose

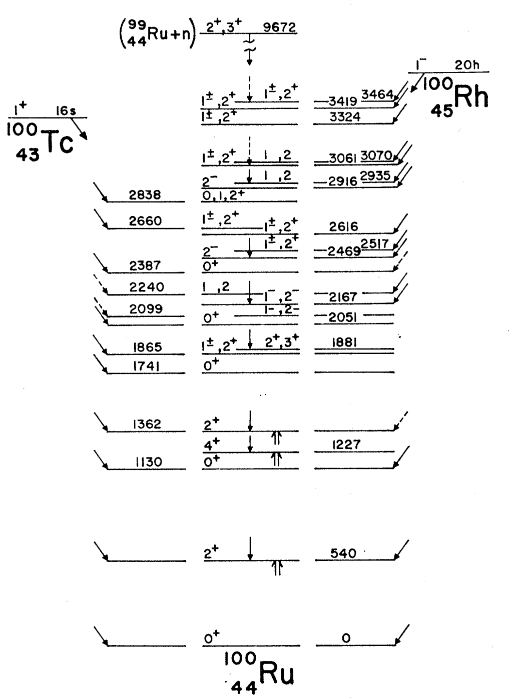

FIG. 14. ^{100}Ru levels observed in the decay of ^{100}Tc and ^{100}Rh. Slanted arrows indicate direct β-ray (and/or electron-capture) feeding of that state from the respective parents. In the center column, double arrows indicate states that have been populated by Coulomb excitation (Ref. 8), and single arrows indicate levels believed to be populated by reported (Ref. 9) primary (n,γ) transitions.

that the 2121- and 2299-keV γ rays terminate at the 540-keV first excited state. The 2299-keV transition cannot feed any of the known states above 540 keV since the β-disintegration energy of ^{100}Tc is $\approx$3.37 MeV. While energetically the 2121-keV γ ray can be placed as feeding the 1130-keV state, the implied $\approx$120-keV β transition would have a log$ft \leq 4.0$, making this hypothesis extremely unlikely. Hence, states are suggested at 2660 and 2838 keV. Support for the former is given by a 2659.5-keV γ ray observed in singles data.

The remaining γ rays (1560, 1701, 1875, and 2128 keV) are too weak to be observed in our ^{100}Tc coincidence data. It is probable that the 1560- and 1701-keV transitions are identifiable with γ rays having very nearly the same measured energy in the ^{100}Rh decay. Therefore, in Fig. 12 both of these are shown as terminating at the 540-keV state. Since there is no basis for a unique placement of the 1875- and 2128-keV γ rays, they are not shown in the decay scheme.

B. ^{100}Rh

The ^{100}Rh coincidence data clearly show that the 540-, 1130-, 1362-, and 1865-keV states seen in the ^{100}Tc decay are also populated in the decay of ^{100}Rh. Another low-lying state is suggested at 1227 keV by the 687-540-keV cascade. Its energy is sufficiently close to that reported for the 4$^+$ level (1230 keV) observed in Coulomb-excitation studies[8] that these levels are assumed identical.

Additional levels are established at 3324, 3070, 2935, 2916, 2469, 2167, and 1881 keV by the presence of the 2784-, 2530-, 2394-, 1930-, 1627-, and 1342-keV γ rays, respectively, in the coincidence spectrum gated by 540-keV photons. None of the above γ rays was observed to be coincident with any of the transitions which depopulate the 1130-, 1227-, and 1362-keV levels. Confirming evidence in the form of additional cascades and/or ground-state transitions was found for all of the above high-lying states.

The coincidence data indicate a definite 371-1560-keV cascade and a probable 229-1701-keV cascade. The fact that these two energy sums are nearly identical with the measured energy of the 1930-keV γ ray suggests that these cascades parallel the 1930-keV transition, populating intermediate states at 2099 and 2240 keV, respectively. The proposed 2099-keV level is confirmed by the presence of lines at 371 and 1560 keV in the spectra gated with either 540- or 446-keV photons. (The 446-keV transition has been shown to terminate at the 2469-keV level.) Additional support for the 2240-keV level is given by the fact that both the 446- and 540-keV transitions were present in the spectrum coincident with the 229-keV γ ray. The order of the above two cascades is determined by the measured relative intensities of the respective γ rays. Moreover, it is probable that the 1560- and 1701-keV transitions (but not those of energy 371 and 229 keV) were also observed in the ^{100}Tc decay.

TABLE V. Comparison of $^{99}Ru(n, \gamma)^{100}Ru$ data (Ref. 9) and the present (β, γ) data in cases where common levels appear to be involved. All energies are in keV.

(n, γ) data[a] Primary transition	Implied level energy[c]	Observed γ rays that may deexcite level E_γ	I_γ	(β, γ) data[b] Known major deexcitation transitions E_γ	I_γ (rel.)[d]
9134.8	537.2	539.8	15.2	539.6	...
8446.6	1225.4	687.1	6.1	686.9	...
8309.8	1362.2	1362.3	1.2	1362.1	1.04
		822.9	1.4	822.5	1.40
7790.1	1881.9	...	...	1341.6	...
7506.2	2165.8	2172.5	0.21	2167.0	0.36
		1627.8	3.1	1627.5	3.10
		303.2	0.19	302.2	0.16
7203.9	2468.1	1928.4	0.38	1929.7	0.38
		(1103.5)[e]	1.87	1107.1	0.42
		(591.7)[e]	0.47	588.2	0.13
6754.3	2917.7	2374.2	0.52	2376.1	0.52
		(1557.4)[e]	1.21	1553.4	0.31
		...	...	446.2	0.17
6608.1	3063.9	3061.5	0.12	3060.6	...
6209.1	3462.9	(3465.7)[e]	0.17	3464.0	0.014
		403.9	0.64	403.5	0.64

[a] From Ref. 9.
[b] Present work.
[c] Based on an assumed neutron binding energy of 9672.0 keV.
[d] The group of intensities for each level is normalized to the intensity of a selected (n, γ) line.
[e] Probable doublet, based on intensity and energy comparison with (β, γ) data.

A level is indicated at 2516 keV by the observed 1386-591-540- and 651-1326-540-keV cascades. The data also suggest that the 1977-keV γ ray is coincident with the 540-keV transition. The weak 2516-keV γ ray observed in singles data is assumed to be the ground-state transition.

The 3464- and the 3419-keV γ rays are of such high energy that they must be ground-state transitions, implying states at these respective energies. Additional levels must exist at 3061 and 2616 keV, since the γ rays of these energies were definitely absent from the integral coincidence spectrum.

The weak γ rays of energy 1848, 1512, and 1201 keV are assumed to be identifiable with the transitions of almost precisely the same energy observed in the decay of ^{100}Tc; i.e., the 2387-, 2051-, and 1741-keV states that are fed by the ^{100}Tc parent appear to be also populated in the decay of ^{100}Rh. On the basis of excellent energy fit, the weak 500- and 775-keV γ rays are assumed to feed the 1741-keV state from the 2516- and 2240-keV levels, respectively. Also, the 466-keV γ ray fits energetically between the 2516- and 2051-keV levels; in fact, some evidence for the 466-1512-keV cascade was observed in the coincidence data.

A few of the γ rays observed in singles data are of such low intensity that they could not be discerned in any of the coincidence spectra. Most of these transitions can be placed between already established states. Only the 1996- and 2545-keV γ rays are not included in the proposed decay scheme (Fig. 13).

V. CORRELATION OF OBSERVED ^{100}Ru LEVELS WITH (n, γ) DATA

As recognized by Anton'eva *et al.*,[4] several of the reported[9] high-energy $Ru(n, \gamma)$ transitions fit energetically as primary capture transitions to known levels of ^{100}Ru. It is also apparent that several of the low-energy (n, γ) lines are identifiable with γ rays seen in the ^{100}Tc and ^{100}Rh decay studies. Table V summarizes the main results of our search for possible correlations between the present data and the $Ru(n, \gamma)$ data. Other observed (n, γ) transitions that may be identifiable with γ rays seen either in the ^{100}Tc or ^{100}Rh decay are as follows (energies in keV): 2659.3 (versus 2659.5, ^{100}Tc), 2298.3 (versus 2298.6, ^{100}Tc), 2530.4 (versus 2530.2, ^{100}Rh), and 3416.7 (versus 3419.0, ^{100}Rh).

From the various energy sums involving our level energies and the associated primary (n, γ) transitions, we obtain a neutron binding energy for ^{100}Ru of approximately 9672 keV, which compares favorably with the recently reported[12] value of 9671.1±6.2 keV.

VI. SPIN ASSIGNMENTS

The analysis of the ^{100}Tc 591-540-keV angular-correlation data indicates that this cascade is of the type 0-2-0. Since the ground state is 0^+, the 540-keV

[12] C. Maples, G. W. Goth, and J. Cerny, Nucl. Data, Sec. A **2**, 429 (1966).

TABLE VI. K-conversion coefficient data for ^{100}Rh transitions, based on the internal-conversion intensities of Koike *et al.* (Ref. 3) and the present γ-ray intensities. The values for α_K are normalized to the theoretical α_K value for the 538.6-keV $E2$ transition. Where more than one transition contributes significantly to an observed internal-conversion line, a composite conversion coefficient is calculated unless known multipolarities are involved. The multipliers in the headings multiply the quantity.

E_γ	I_γ (rel.) ($\times10^{-2}$)	I_K (rel.) (Ref. 3)	α_K ($\times10^3$)	Implied multipolarity
370.6	1.4±0.7	1.8[a]	13.0±7.5	$M1$, $E2$
446.2	37.6±1.3	24±2	6.4±0.6	$M1$, $E2$
539.6	263	100	3.8[b]	$E2$[c]
588.2	13.8±0.7 }	3.1±0.3	1.20±0.15	$E1$
590.8	4.8±0.7 }		3.0[b]	$E2$[c]
650.9	1.7±0.3 }	0.7[a]	2.2±0.6	$M1$, $E2$
654.5	1.4±0.3 }			$M1$, $E2$
686.9	2.2±0.2	0.7[a]	3.2±0.9	$M1$, $E2$
734.7	0.8±0.3 }	0.79±0.09	2.0±0.4	
736.9	0.3±0.2 }			
748.5	2.8±0.2 }			$M1$, $E2$
822.5	67.6±3.4	10±1	1.48±0.18	$M1$, $E2$
1034.3	4.8±0.2	0.23±0.08	0.48±0.17	$E1$
1107.1	44.5±1.3	1.5±0.3	0.34±0.12	$E1$
1341.6	16.2±0.7	1.1±0.3	0.68±0.19	$M1$, $E2$
1362.1	50.4±1.3	1.9±0.3	0.38±0.11	$M1$, $E2$
1553.4	69.0±1.8	1.2±0.2	0.17±0.03	$E1$
1929.7	40.7±1.3	0.45±0.06	0.11±0.02	$E1$
2376.1	117±8	0.8±0.1	0.07±0.01	$E1$

[a] Error not quoted in Ref. 3. An error of ±25% has been assumed in the calculation of α_K.
[b] Theoretical value from Ref. 14.
[c] Known from γ-γ angular-correlation results.

state must be 2^+, an assignment supported by angular-correlation studies[2,3] of cascades emitted in the decay of ^{100}Rh, by recent Coulomb-excitation experiments,[8] and by the energy-level systematics of even-even nuclei.[13] Similarly, the 1130-keV state must have $J^\pi=0^+$. This assignment is consistent with the observed absence of a γ transition to the ground state.

With the 539.6-keV transition multipolarity established as $E2$, one can use the corresponding theoretical K-conversion coefficient[14] [$\alpha_K(E2;\ 539\ \text{keV})=3.8\times10^{-3}$] to normalize the ^{100}Rh conversion-electron line intensities[3] to the present ^{100}Rh γ-ray intensities and thus obtain K-conversion coefficients for the transitions observed by Koike *et al.*[3] The results are shown in Table VI. A similar analysis has been made by Anton'eva *et al.*,[4] whose results agree essentially with ours except that (1) we have taken into account the multiplet nature of certain conversion lines, and (2) we have assigned the 371-keV transition as $M1$, $E2$ rather than $E1$. In the case of the 589-keV doublet, we have made use of the known multipolarity of the 590.8-keV transition (pure $E2$) in order to obtain an α_K value for the 588.2-keV transition, which appears to be $E1$ on this basis. In the case of the 653-keV doublet, the composite α_K value is consistent with $M1$, $E2$, which strongly suggests that the 650.9- and 654.5-keV transitions are both $M1$, $E2$ since the γ-ray transition intensities are nearly equal. (Note: The notation $M1$, $E2$ used here and in Table VI signifies consistency with either of these multipolarities or with $M1+E2$, reflecting the fact that throughout the energy range 0.4–2.4 MeV at $Z=44$, the $M1$ and $E2$ α_K values are nearly equal.)

The 1362-keV level has been shown to be 2^+ through Coulomb-excitation work[8] and angular-correlation studies[2,3] of the decay of ^{100}Rh. There is no doubt that the same 1362-keV state is observed in the decay of both ^{100}Tc and ^{100}Rh since the energies and branching ratios observed in the two cases are in good agreement. Furthermore, the angular-correlation measurements for the 822-540-keV cascade in the decay of both ^{100}Tc and ^{100}Rh (Refs. 2 and 3) are consistent with a $2(1,2)2(2)0$ correlation.

Our angular-correlation measurements also imply $J^\pi=0^+$ for the 1741-, 2051-, and 2387-keV levels. All three of these states decay only to lower-lying 2^+ levels, in support of the proposed 0^+ assignments. Also, none of these states is observably populated by direct (n,γ) transitions[9] from the capture state $(2^+, 3^+)$, which is consistent with $J^\pi=0^+$ since $E2$ transitions are rarely observed in the primary (n,γ) spectrum.

The multipolarities implied by the α_K data, combined with the results of earlier ^{100}Rh angular-correlation studies,[2,3] establish that the 2469- and 2916-keV levels are both 2^-. Our observation of weak ground-state transitions from each of these levels does not conflict with the 2^- assignments. The Weisskopf formulas[11] predict $E1/M2$ branching ratios of $\approx10^5$

[13] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).
[14] R. S. Hager and E. C. Seltzer, California Institute of Technology Report No. CALT-63-60, 1967 (unpublished).

in each of these cases, but since $E1$ hindrances of $\geq 10^3$ are quite common, our observed branching ratios of $\approx 10^2$ seem entirely reasonable.

The α_K data indicate $E1$ multipolarity for the 588- and 1034-keV transitions, implying $J^\pi=(1, 2, 3)^+$ for the 1881-keV level. However, the 1^+ possibility is eliminated by the fact that this state decays by $M1$, $E2$ transitions to the 1227-keV 4^+ state. Of the two remaining choices, 3^+ seems favored by the nonobservation of this state in the decay of ^{100}Tc (which, as pointed out below, must be 1^+).

The 2099-keV state is fed in the ^{100}Rh decay from the 2469-keV (2^-) state by an $M1$, $E2$ transition and decays only to 2^+ states, indicating $J^\pi=(1, 2, 3)^-$. It is probable that this state is directly β fed in the decay of ^{100}Tc (1^+), which makes the 3^- assignment unlikely.

The 2167-keV level, which is fed in the ^{100}Rh decay from the 2915-keV (2^-) state by an $M1$, $E2$ transition, is observed to decay to both 0^+ and 2^+ states. Thus, J^π is restricted to 1^- or 2^-. The 1^- assignment seems the more likely because of the relative strength of the ground-state transition.

One can narrow the range of possible J^π values for the other states by applying the usual γ-decay selection rules to the transitions that connect these levels with states of established spin-parity and by considering the log*ft* values of the decay branches from the 1^+ and 1^- parents (see below). The possible values are shown in Figs. 12–14. It should be noted that all of the indicated assignments are consistent with the multipolarities implied by the internal-conversion data and also with the assumption that the observed[9] primary (n, γ) transitions are of dipole character.

The ground state of ^{100}Tc is assigned as 1^+ in view of the unquestionably *allowed* character of the β transitions to the first two 0^+ states of ^{100}Ru.

As recognized in previous studies,[2–4, 10] the ^{100}Rh log*ft* values for the β^+ branches to the 0^+ ground state, to the 540-keV 2^+ state, and to the 2916-keV 2^- state require a spin-parity of 1^- or 2^- for the parent state. The 1^- possibility is strongly favored by our deduced K-capture/positron ratio for the decay branch to the 1130-keV 0^+ state. This ratio was evaluated as follows: The observed relative intensity of the 590.8-keV γ ray gives a direct measure of the total feeding of the 1130-keV level. The respective amounts of direct γ feeding and β^+ feeding are obtainable from the spectrum gated with the (588, 591)-keV doublet, using the coincidence intensities of the 2194-, 1386-, 735-, and 511-keV lines, all of which arise from 591-keV gates. The rest of the population of the 1130-keV level is then attributed to electron capture, about 85% of which is predicted to be K capture. In this way, we obtain a "raw" value for ϵ_K/β^+ (1130 keV) of ≈ 1.3. However, in view of the source-detector geometry used, we estimate that this value is 10–20% high because some of the high-energy positrons were not stopped in the absorbers surrounding the source. After correction for this effect, our ϵ_K/β^+ (1130 keV) value is clearly in much closer agreement with the value 0.87 predicted[11] for a $\Delta J=0,1$ (yes) transition than with the value 2.9 predicted for a $\Delta J=2$ (yes) transition.

Our deduced β^+ intensity to the 1130-keV level is almost a factor of 2 smaller than the value of 0.61% obtained by Marquez.[10] This difference may result from the fact that in β-spectrum analysis, the intensities of weak, inner groups are difficult to measure accurately and are often overestimated because the observed spectrum contains a contribution from degraded electrons. In support of this hypothesis, it is clear from our work that the reported β^+ transition[10] to a level at ≈ 2.1 MeV is weaker than Marquez's Fermi plot indicates (0.18%, log$ft=6.6$) by roughly a factor of 10. Another potential source of error in the Marquez analysis is the possibility that there is a weak β^+ transition to the 1362-keV (2^+) level, which could contribute part of the intensity of his 1260-keV β^+ group. Although we obtain nearly exact γ-ray intensity balance at the strongly excited 1362-keV level, our over-all uncertainty in this balance does not exclude 0.3% β^+ feeding.

Our deduced spin-parity assignment for 20-h ^{100}Rh is supported by an earlier result obtained by Evans and Naumann.[15] Their measurement of the anisotropy of a γ-γ cascade emitted in the ^{100}Pd$\rightarrow$^{100}Rh decay indicates that 1^- is a much more likely value than 2^- for the ground-state assignment.

VII. DISCUSSION

Semiquantitatively, the lowest-lying states in ^{100}Ru appear to correspond well to the level sequence predicted by the simple vibrational model. According to this model,[13,16] the lowest 2^+ state should be a one-phonon quadrupole vibration, and the two-phonon quadrupole excitation should produce a (0^+, 2^+, 4^+) triplet of states centered at approximately twice the energy of the 2^+ one-phonon state. Thus, one associates the 540-keV 2^+ level with the one-phonon vibration and the 1130-keV 0^+, 1227-keV 4^+, and 1362-keV 2^+ states with the two-phonon triplet. Higher-lying states are expected[16] to result from higher-order quadrupole excitations, from octupole vibrations, and from the coupling of quadrupole and octupole vibrations, as well as from individual two-quasiparticle and four-quasiparticle excitations. At the present time there is no reliable way to identify any of the experimental levels above 1.5 MeV with members of particular vibrational multiplets.

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[15] J. S. Evans and R. A. Naumann, Phys. Rev. **138**, B1017 (1965).
[16] O. Nathan and S. G. Nilsson, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Co., Amsterdam, 1965), Vol. 1, p. 608.

The vibrational description encounters certain difficulties with respect to transition probabilities. The model predicts that the reduced $E2$ transition rates from the two-phonon states to the one-phonon level should be twice that from the one-phonon state to the ground state. McGowan *et al.*,[8] using the Coulomb-excitation technique, have measured the $B(E2, J\rightarrow 2)/B(E2, 2\rightarrow 0)$ ratios for ^{100}Ru and other nearby doubly even Ru nuclei, and have found the values to be significantly less than 2. In fact, in the case of ^{100}Ru, the measured $B(E2, 4\rightarrow 2)/B(E2, 2\rightarrow 0)$ value of 1.27 ± 0.14 is in much better agreement with the value of 1.43 predicted by the rotational model[17] than with the vibrational prediction.

Although the first 0^+, 2^+, and 4^+ states clearly do not exhibit an $I(I+1)$ energy dependence, a modified rotational interpretation may have some validity beyond the above $B(E2)$ considerations. A recent generalization of the rotational description, called the variable-moment-of-inertia (VMI) model,[18] has been successful in describing many properties of doubly even nuclei. The VMI model assumes changes in the moment of inertia, as a function of angular momentum, as one progresses up the ground-state rotational band. Each nucleus is characterized by two parameters: I_0 (the ground-state moment of inertia) and a softness parameter σ which reflects the spin-dependent change in the moment of inertia. The suggested region of validity for the VMI model, defined in terms of the ratio of the energies of the first 4^+ and 2^+ states $(2.23\leq E_4/E_2\leq 3.33)$, includes nuclei in the deformed region, as well as many of those near closed shells. For ^{100}Ru, $E_4/E_2=2.28$, which is just inside the above range. The corresponding value of the softness parameter σ is approximately 200, whereas σ is <1 for strongly deformed nuclei. One test of the VMI interpretation of ^{100}Ru would be the location (still unknown) of the 6^+ state [*Note added in proof.* G. T. Ewan and G. I. Andersson (private communication), utilizing the $(\alpha, 2\eta, \gamma)$ reaction, have recently established the energy of the 6^+ state to be 2076 keV.] which the model predicts at $\approx$2050 keV (for E_4/E_2 of 2.28). Some insight into this question can be gained from nearby ^{102}Ru, where a 6^+ state has been identified[19,20] at 1872 keV, in good agreement with the VMI prediction of $\approx$1850 keV. It should be pointed out, however, that $E_4/E_2=2.33$ for ^{102}Ru, implying a softness of $\sigma\approx 25$ for this nucleus, which places it considerably farther toward the deformed category than is ^{100}Ru.

From a microscopic point of view, the ground state of doubly even ^{100}Ru may be characterized by the proton (π) and neutron (ν) configuration

$$\{[a_1(p_{1/2})^2(g_{9/2})^4+a_2(g_{9/2})^6]^{\pi}{}_{0^+} +[b_1(d_{5/2})^6+b_2(d_{5/2})^4(g_{7/2})^2+b_3(d_{5/2})^4(s_{1/2})^2 +b_4(d_{5/2})^4(d_{3/2})^2+b_5(d_{5/2})^2(g_{7/2})^4 +b_6(d_{5/2})^2(g_{7/2})^2(s_{1/2})^2+\cdots]^{\nu}{}_{0^+}\}.$$

The lowest-lying states should be formed by rearrangements and/or recouplings of pairs in this configuration. Thus, it is not difficult to qualitatively account for the rather large number of experimentally observed 0^+ levels; one can expect four 0^+ states from variations in the pairwise occupancy of the $d_{5/2}$ neutron orbital alone.

From a shell-model point of view, one would conclude that the ^{100}Tc configuration is mainly a 0^+ core coupled to $[(g_{7/2})^{\pi}(g_{9/2})^{\nu}]_{1^+}$, the lowness of the $\log ft$ value (4.7) for the ground-state β transition presumably reflecting a dominant $g_{7/2}\rightarrow g_{9/2}$ single-particle contribution. However, this picture is clouded by the failure of the model to account for the 1^- spin of 20-h ^{100}Rh. Application of the Brennan and Bernstein coupling rules[21] predicts a ground-state spin-parity of 2^-, and there is no pair of orbitals close to the Fermi surface that yield 1^-. Hence, it appears that the nucleon configurations within the relevant subshells are more complex than conjugate pairs coupled to an odd nucleon. Such a view is supported by empirical data on the adjacent odd-mass nuclei. For example, the simple shell model would predict that the lowest-lying states in the nearby odd-proton nuclei should be those arising from an odd proton occupying one or the other of the $p_{1/2}$ and $g_{9/2}$ orbitals. However, in many cases a $\frac{7}{2}^+$ level has been observed very close in energy to the lowest $\frac{9}{2}^+$ state. Similarly, in the nearby odd-neutron nuclei, where the lowest shell-model states are $d_{5/2}$, $s_{1/2}$, $d_{3/2}$, and $g_{7/2}$, one observes low-lying $\frac{1}{2}^+$ and $\frac{3}{2}^+$ states that, respectively, have very little $s_{1/2}$ and $d_{3/2}$ character. These "extra" states clearly involve the coupling of three or more nucleons, and it appears that some of them contain large core-excitation admixtures. In the case of ^{100}Rh, we have found that there are various sets of simple multiparticle configurations, involving only the valence nucleons, that are consistent with the limited amount of empirical data on the low-lying levels (cf. Ref. 11). However, a uniquely valid formulation of this problem must await further theoretical and experimental investigations.

A significant feature of the ^{100}Tc decay that needs to be explained in subsequent theoretical studies is the anomalous β branching to the 0^+ and 2^+ states. Typically, in the intermediate-mass region, the β

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transitions of type $1^+ \to 2^+$(one-phonon) are 2–10 times slower than the $1^+ \to 0^+$ ground-state transitions,[11] an effect that is usually attributed to the collective vibrational character of the 2^+ state. However, in the ^{100}Tc$\to$^{100}Ru decay, the reduced transition probability to the first 2^+ state is ≈ 100 times less than that to the ground state. Similarly, the transition probability to the second 0^+ level (1130 keV) is ≈ 100 times greater than that to the second 2^+ level (1362 keV). Since, in the vibrational-model description, both of these latter two levels are two-phonon states, it is clear that the dissimilar branching is not attributable to a simple difference in vibrational character. We suspect that a satisfactory explanation of the highly retarded decay to the first two 2^+ levels will need to take into consideration the detailed shell-model configurations of both the parent and daughter states.

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Level Scheme of ^{153}Sm Based on (n, γ), (n, e^-), and β-Decay Experiments*

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The ^{152}Sm$(n, \gamma)^{153}$Sm spectrum was measured with the Argonne bent-crystal spectrometer and with a Ge(Li) detector at the in-pile facility at the Argonne CP-5 research reactor. The low-energy bent-crystal spectrum consisted of 251 γ transitions associated with thermal-neutron capture in ^{152}Sm, with energies between 28 and 1041 keV. The γ-ray intensities were normalized to the previously established intensity of the 103-keV line in ^{153}Eu from the β decay of ^{153}Sm. The energies and intensities of 24 other lines associated with this β decay are also given. The high-energy (n, γ) spectrum, containing 23 lines between 4.5 and 5.9 MeV, was obtained with a Ge(Li) detector. The neutron binding energy of ^{153}Sm was found to be 5869.3 ± 2.0 keV. The conversion-electron spectrum, measured with the high-resolution magnetic spectrometer at Munich, was used to obtain K and L conversion coefficients and corresponding multipole assignments for 37 of the low-energy γ transitions. The γ spectrum in ^{153}Sm following β decay of ^{153}Pm was measured with Ge(Li) and Si(Li) detectors. The source was made at Darmstadt through the ^{154}Sm$(\gamma, p)^{153}$Pm reaction. The (n, γ), (n, e^-), and β-decay experiments were combined to develop the level scheme of ^{153}Sm, in which unique spin and parity assignments are made for 13 of the 28 levels below 750 keV. The energy (keV) and J^π of the first 28 levels are: 0.000, $\frac{3}{2}^+$; 7.535, $\frac{5}{2}^+$; 35.843, $\frac{3}{2}^-$; 53.533, $\frac{7}{2}^+$ or $(\frac{5}{2}^+)$; 65.475, $\frac{9}{2}^+$ or $\frac{7}{2}^+$ or $\frac{5}{2}^+$; 90.874, $\frac{5}{2}^-$; 112.954, $\frac{9}{2}^+$ or $\frac{7}{2}^\pm$ or $\frac{5}{2}^\pm$; 127.298, $\frac{3}{2}^-$; 174.17, $\frac{7}{2}^-$; 182.90, $\frac{5}{2}^-$; (194.65), $\frac{5}{2}^\pm$ or $\frac{7}{2}^+$; 262.33, $\frac{7}{2}^+$ or $(\frac{5}{2}^+)$; (265.93), $\frac{7}{2}^-$ or $(\frac{5}{2}^\pm)$; 276.71, $\frac{3}{2}^+$; 321.11, $\frac{3}{2}^+$; 356.69, $\frac{5}{2}^+$; 362.29, $\frac{5}{2}^+$; (371.04), $\frac{9}{2}$ or $\frac{7}{2}$; 405.46, $\frac{3}{2}^-$; 414.91, $\frac{1}{2}^+$ or $\frac{3}{2}^+$; 447.07, $\frac{5}{2}$ or $\frac{7}{2}$; 450.04, $\frac{5}{2}$ or $\frac{7}{2}$; 481.08, $\frac{3}{2}^+$; 524.36, $\frac{5}{2}$; 630.20, $\frac{3}{2}^{(-)}$; 695.83, $\frac{1}{2}^{(+)}$ or $\frac{3}{2}^{(+)}$; 734.90, $\frac{5}{2}$; and 750.32, $\frac{1}{2}$ or $\frac{3}{2}$. The parentheses around a level energy or spin assignment mean that this value is less well established or is less probable if there is a choice. Of special interest is the very low-energy (7.53 keV) first excited state with $J^\pi = \frac{5}{2}^+$, which appears to be the second member of the strongly distorted ground-state rotational band. A good match between the theoretical predictions of the Nilsson model and the observed γ-ray branching ratio was obtained when nine of the eleven levels below 200 keV were assigned to a positive-parity, $K = \frac{3}{2}$, ground-state rotational band and two negative-parity, $K = \frac{3}{2}$, rotational bands with band heads at 35.84 and 127.30 keV.

I. INTRODUCTION

The level scheme of ^{153}Sm is of special interest because this nucleus falls in the transition region between groups of nearly spherical nuclei ($A \leq 150$) and deformed nuclei ($A \geq 154$). The level schemes of the two adjacent even-Z, even-N nuclei, ^{152}Sm and ^{154}Sm, exhibit distorted but easily recognized ground-state rotational bands which suggest moderately strong deformations for these nuclei. The ^{153}Sm nucleus is in fact the lightest even-Z, odd-N samarium isotope that can, with reasonable certainty, be expected to exhibit a level scheme consistent with the Nilsson model for an

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