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Radiative decay of neutron resonant states in ruthenium*

Karim Rimawi and J. B. Garg
State University of New York, Albany, New York

R. E. Chrien, G. W. Cole, and O. A. Wasson
Brookhaven National Laboratory, Upton, New York 11973
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γ rays following slow-neutron capture in natural ruthenium have been studied. Spin and isotopic assignments for resonances have been made based on high- and low-energy γ-ray transitions. In the case of the product nuclei ^{100}Ru- ^{102}Ru, the present (n,γ) studies extend our knowledge of the level schemes to energies higher than previously available from β-decay studies of Rh and Tc isotopes. A notable feature of the data is a relatively high concentration of radiation strength between 6.5 and 7.0 MeV for both ^{100}Ru and ^{102}Ru. $M1$ enhancement could be ascribed to a doorway state in neutron capture leading to spin-flip transitions of the $g_{7/2} \rightarrow g_{9/2}$ type.

[NUCLEAR REACTIONS ^{99,101}Ru(n,γ) $E_n=0.0253$ to 230 eV, deduced resonance spins, isotopic identifications, partial widths $\Gamma_{\gamma\lambda f}$; ^{100,102}Ru levels, spin, and parities.]

I. INTRODUCTION

The study of resonance neutron capture in Ru isotopes was undertaken as a continuation of a program for the investigation of resonance neutron capture near the mass region $A=100$.[1] The low-energy neutron resonances of ruthenium have been recently investigated by Coceva *et al.*,[2] and by Priesmeyer and Jung.[3] Both groups report a number of resonances which are not isotopically identified. The identification of these resonances is possible through their γ decay whenever the low-lying states are known for the product nuclei.

Most of the information available on low-lying levels of Ru isotopes comes from β-decay studies of Rh and Tc isotopes.[4-7] Hratsnik *et al.*[8,9] report the levels of ^{103}Ru and ^{105}Ru from thermal neutron capture on ^{102}Ru and ^{104}Ru. Levels in these two nuclei were also investigated by Fortune *et al.*[10] using the (d,p) reaction. The levels of ^{103}Ru were also investigated through the (d,t) reaction by Diehl *et al.*[11]

As reported in Refs. 2 and 3, most of the low-energy neutron resonances belong to ^{99}Ru and ^{101}Ru. The known low-lying levels in ^{100}Ru and ^{102}Ru are those obtained from β-decay studies.[5-7] Since these are limited by the Q value for the β decay, the (n,γ) study extends our knowledge of the levels of these nuclei to higher energies, and in some cases enables us to determine the spins of these levels.

Information on the capture mechanism can often be extracted from resonance-capture studies. In this case we observe a large enhancement of $M1$ transition strength that could be indicative of an $M1$ giant-resonance effect. A preliminary report of this study has been presented previously.[12]

II. EXPERIMENTAL CONDITIONS

The fast chopper facility of the High Flux Beam Reactor of Brookhaven National Laboratory was used in these measurements. A sample of 150 g of natural Ru in powder form was placed in a thin Al annulus surrounding a 4-cm^3 Ge(Li) detector. The detector was placed in the neutron beam with a Pb shadow cone protecting it from being exposed to the direct neutron beam. The flight path was 49 m from the chopper to the detector.

Three different chopper speeds were used to cover the available neutron energy range. Five runs were taken with a chopper speed of 10 000 rpm, and one run each with chopper speeds of 6000 rpm and 3000 rpm, which gave better statistics for lower-energy resonances. Two thermal-neutron-capture runs with a chopper speed of 1500 rpm using the same ring geometry showed spectra which were dominated by background lines mostly from capture in Fe, Cu, Al, and Ge arising from capture in the detector and its structural supports. The thermal run was repeated with the detector outside the beam, but though the γ rays from ruthenium showed up more strongly in the observed spectrum, they were still weak compared to background lines. It was felt, therefore, that the thermal run was not adequate for normalizing the resonance-capture intensities to absolute values, and another run with a chopper speed of

15 000 rpm was taken using a composite sample of ruthenium and gold foils at a flight path of 22 m. Known transitions in the decay of the 5-eV Au resonance were used to normalize the Ru intensities.

In the above runs both γ pulse-height and neutron time-of-flight information were recorded separately in a two-parameter time-of-flight analysis system.[13] Spectra for γ rays with energy deposited in the detector within the range 2.5–8.6 MeV were studied at a gain of 3 keV/channel.

A set of five runs with chopper speed of 12 000 rpm was further taken recording the low-energy γ-ray spectra for γ rays with energy less than

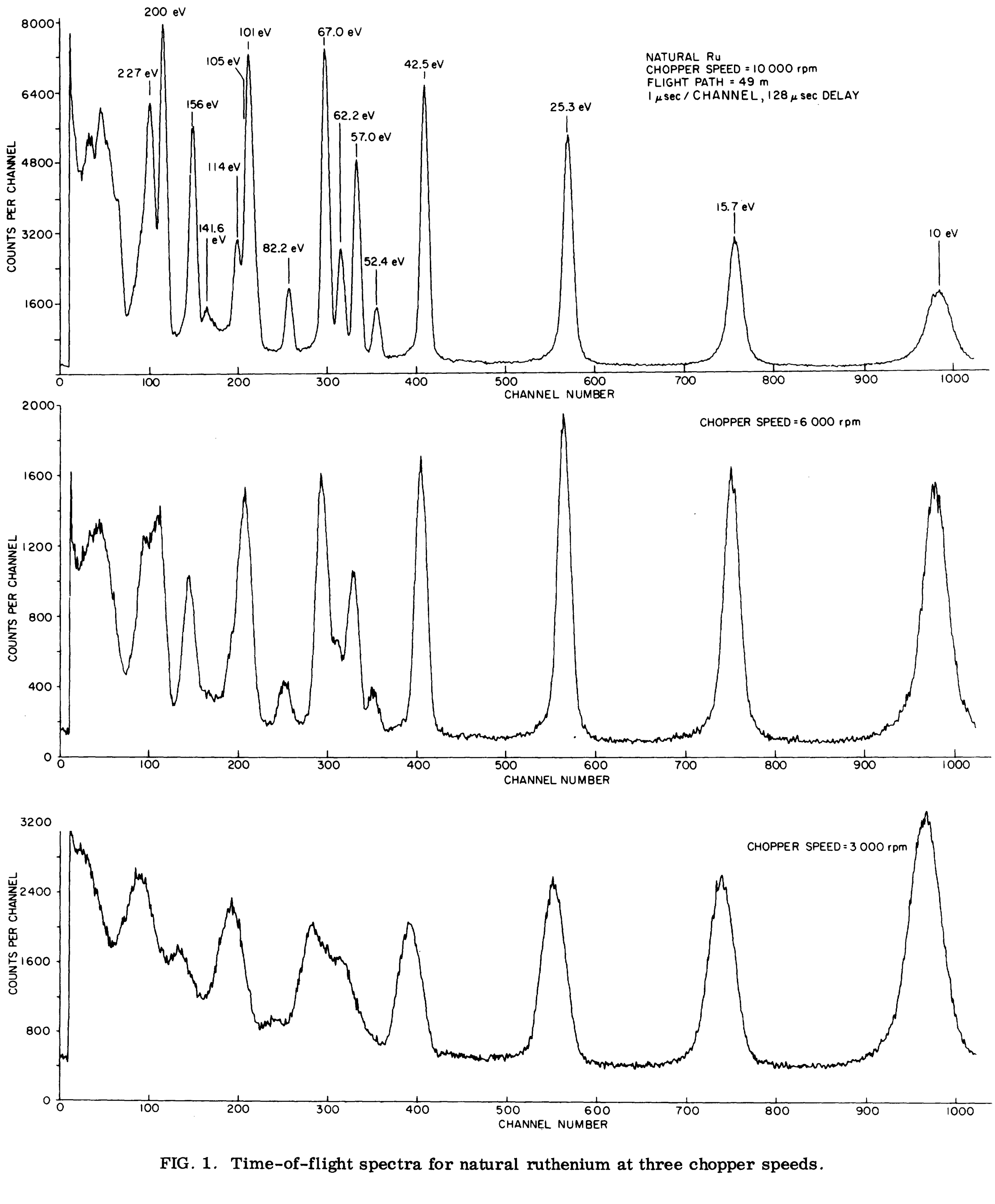

FIG. 1. Time-of-flight spectra for natural ruthenium at three chopper speeds.

1.5 MeV at a gain of 0.75 keV/channel. In these runs the detector was placed outside the neutron beam and a ^{6}LiH shield was used.

III. DATA REDUCTION

The time-of-flight (TOF) spectra obtained with the three different chopper speeds for the high-energy runs are shown in Fig. 1. The TOF scan limits of the peaks at 10.0, 15.7, 25.3, 42.5, 52.4, 57.0, 62.2, and 82.2 eV include only one resonance each as reported in Refs. 2 and 3. The peak at 112 eV which is only partially resolved from the 101-eV peak also includes one resonance. Of the above listed resonances, the resonances at 25.3, 57.0, and 82.2 eV belong to ^{99}Ru, while the rest belong to ^{101}Ru. The resonance at 10 eV had not been previously isotopically identified.

The remaining TOF peaks include two or more resonances each. Some of these had not been isotopically identified,[2,3] for example, the unassigned resonance at 65.66 eV, near the 66.8-eV resonance of ^{101}Ru. This case will be discussed below.

The γ-ray spectra are shown in Figs. 2 and 3 for several different scan regions. These spectra were used to extract the energies and intensities for the different transitions by least-squares fitting the individual peaks assuming a Gaussian shape for the peak.[14] The energies of Rasmussen *et al.*[15] for thermal-neutron-capture γ rays were used to set the energy calibration in this experiment.

Absolute transition probabilities were obtained from the mixed-sample run of Ru and Au. Following a suggestion of Carpenter,[16] the number of γ rays observed for a certain transition from resonance state i to low-lying state f, can be expressed as

$$N_{\gamma if} = K A_i \phi_i \lambda_{\gamma if} \epsilon_f ,$$

where K is a constant, A_i is the probability that a neutron is captured in state i, ϕ_i is the incident neutron flux, $\lambda_{\gamma if}$ is the absolute transition probability in photons/neutron capture, and ϵ_f is the relative detector efficiency.

The neutron-capture probability A_i in the different resonances was calculated using the resonance parameters tabulated in Brookhaven National Laboratory Report No. BNL-325.[17]

The neutron flux was measured in a separate experiment, under similar conditions, in which the intensity of the 477-keV line in the $^{10}B(n, \alpha\gamma)^7Li$

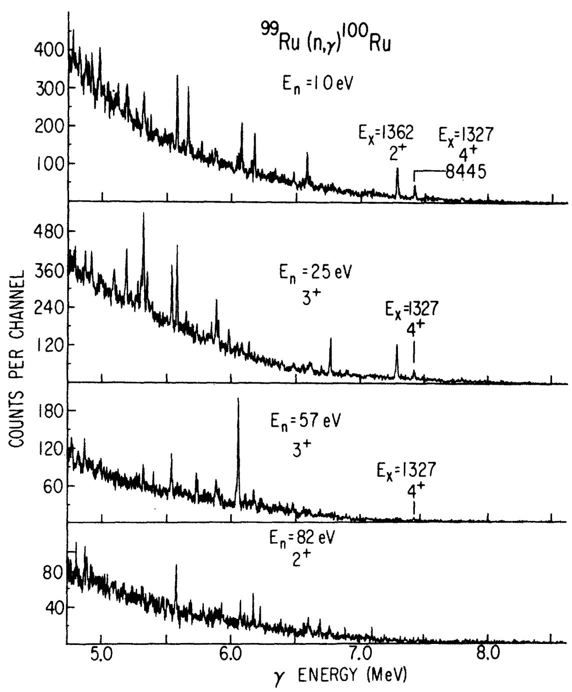

FIG. 2. Several resonance spectra identified with capture in ^{99}Ru. The energy scale denotes energy deposited in the detector; the prominent peaks are two-escape peaks at $E_\gamma = 1.022$ MeV.

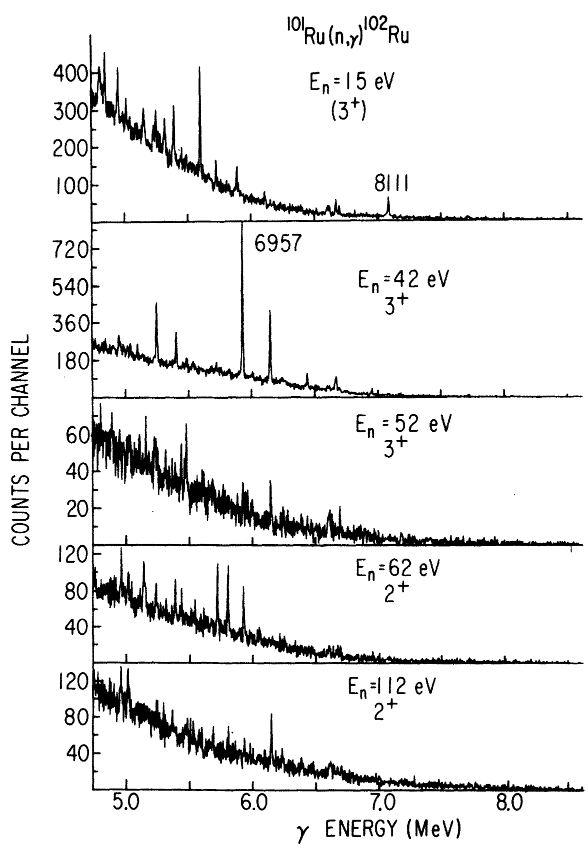

FIG. 3. Resonance spectra assigned to ^{101}Ru capture. The energy scale is similar to Fig. 2.

TABLE I. Partial widths for $^{99}Ru(n,\gamma)^{100}Ru$.

				$^{99}Ru(n,\gamma)$							
				E_n = 10.0 eV J = 3		E_n = 25.2 eV J = 3		E_n = 57.1 eV J = 3		E_n = 81.6 eV J = 2	
E_γ (keV)	ΔE (keV)	E_x [a]	J^π [b]	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)
9135.9	1.3	536.8	2^+			0.14	0.05				
8444.7	0.5	1228.0	4^+	0.58	0.11	0.39	0.06	0.24	0.14		
8308.5	1.5	1364.2	2^+	1.86	0.21	1.51	0.09				
7806.0	1.0	1866.7	$1^+, 2^+$	0.30	0.08			0.24	0.15		
7790.8	0.5	1881.9	$2^+, 3^+$			1.33	0.12	0.17	0.14	0.80	0.28
7624.4	1.5	2048.3	0^+			0.23	0.08			0.48	0.26
7611.0	1.5	2061.7		0.77	0.11	0.11	0.08				
7574.9	0.5	2097.8	2^-	0.15	0.08	0.22	0.12	0.18	0.15		
7504.5	0.4	2168.2	2^-	0.22	0.09	0.21	0.06	0.58	0.17		
7202.3	1.2	2470.4	2^-	0.86	0.12			0.86	0.17		
7158.1	2.4	2514.6	2^+			0.45	0.09	0.20	0.15		
7102.7	2.1	2570.0	2, 3	1.16	0.13	0.33	0.10			1.12	0.24
7080.0	0.4	2592.7	2, 3, 4	0.16	0.09			5.26	0.36		
7005.5	0.7	2667.2				0.62	0.11				
6925.5	0.6	2747.2				0.42	0.10				
6908.2	1.7	2764.5				1.08	0.10	0.50	0.21		
6899.6	1.9	2773.1		0.34	0.09	0.12	0.09				
6870.2	1.5	2802.5				0.35	0.11	0.17	0.19		
6839.9	1.5	2832.8	$1^+, 2^+$			0.04	0.11	0.38	0.18		
6795.3	0.6	2877.4		0.43	0.10						
6755.5	0.6	2917.2	2^-			0.28	0.08	1.13	0.20		
6689.9	0.8	2982.8		1.20	0.13	0.30	0.10				
6654.4	0.5	3018.3		0.10	0.10						
6614.6	0.8	3058.1	$1^+, 2^+$					0.43	0.18	0.42	0.31
6602.3	0.9	3070.4	$2^{(-)}$	1.40	0.13	1.76	0.14			2.43	0.35
6562.2	0.5	3110.5		0.14	0.09	1.36	0.12	1.39	0.19		
6371.6	2.1	3301.1		0.18	0.09	0.75	0.13	0.21	0.18		
6346.8	1.5	3325.9	2^+	0.86	0.10			0.81	0.19		
6340.2	2.1	3332.5	(2^+)	0.67	0.10	1.98	0.20				
6325.2	1.2	3347.5		0.10	0.09	0.70	0.17				
6296.1	1.7	3376.6		0.20	0.08	0.42	0.11	0.38	0.21		
6212.3	1.3	3460.4		0.52	0.09	0.93	0.12				
6206.3	0.5	3466.4	2^+	0.33	0.09			0.24	0.18		
5942.4	0.7	3730.3		0.44	0.10	0.56	0.10				
5894.2	2.1	3778.5		0.47	0.09	0.46	0.12	0.71	0.18	0.95	0.33
5797.0	1.1	3875.7		0.36	0.13			0.39	0.18		
5791.8	0.5	3880.9				0.22	0.10	0.72	0.17		
5700.4	1.9	3972.3		0.28	0.11	0.39	0.10			0.89	0.29
5688.3	0.5	3984.4		0.13	0.11	0.32	0.10	0.42	0.20	0.28	0.19
5673.6	0.5	3999.1		0.29	0.08	0.26	0.10				
5623.2	1.0	4049.5						0.45	0.18		
5581.2	1.2	4091.5		0.07	0.11	0.33	0.11				
5570.8	0.9	4101.9				0.40	0.11				
5523.6	2.2	4149.1				0.17	0.10	0.12	0.21		
5486.8	2.1	4185.9		0.29	0.10					1.01	0.32
5416.1	1.0	4256.6		0.22	0.12	0.30	0.10				
5399.2	1.4	4273.5		0.30	0.13	0.28	0.09				
5365.3	0.8	4307.4		0.33	0.12	0.19	0.11				
5336.8	1.6	4335.9		0.48	0.12	0.24	0.10				
5306.3	1.6	4366.4		0.53	0.12					0.82	0.34

TABLE I *(Continued)*

				^{99}Ru (n,γ)							
				$E_n=10.0$ eV $J=3$		$E_n=25.2$ eV $J=3$		$E_n=57.1$ eV $J=3$		$E_n=81.6$ eV $J=2$	
E_γ (keV)	ΔE (keV)	E_x [a]	J^{π} [b]	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)
5296.6	0.9	4376.1		0.52	0.12	0.09	0.11				
5269.1	0.1	4403.6		0.06	0.10			0.82	0.24		
5153.2	0.7	4519.5		0.61	0.15			0.25	0.22		
5142.6	2.8	4530.1		0.35	0.15	0.23	0.11				
5129.0	1.6	4543.7		0.18	0.13	0.13	0.11	0.45	0.21		
5087.1	1.0	4585.6		0.31	0.13						
5071.5	1.0	4601.2		0.48	0.13						
5021.6	1.8	4651.1		0.52	0.14	0.28	0.11	0.42	0.23		

[a] E_x based on $B_n = 9672.7 \pm 0.7$ keV.
[b] J^{π} from Ref. 5 except where discussed in text.

reaction was measured as a function of neutron energy.

The detector efficiency function was determined from the ^{53}Cr$(n,\gamma)^{54}$Cr reaction for thermal neutrons.[18] The absolute intensities for capture in the 4.9-eV resonance in Au were used as a standard for the determination of the constant K in the above equation.[19] The partial widths were then calculated from the absolute transition probabilities and the total radiation widths as given in BNL-325.[17] These are presented in Tables I and II for ^{99}Ru$(n,\gamma)^{100}$Ru and ^{101}Ru$(n,\gamma)^{102}$Ru, respectively. The errors listed in these tables are statistical and do not include errors due to normalization.

Peaks were analyzed down to $E_\gamma \approx 3.5$ MeV, but only those above 5 MeV are listed in Tables I and II. A complete set of analyzed peaks is available in the files of the National Neutron Cross Section Center (NNCSC), Brookhaven National Laboratory. Spectra for the unresolved resonance regions of the neutron time of flight were also analyzed and relative intensities have been determined. These are not shown here, but are available from the NNCSC.

IV. RESONANCE STRUCTURE OF RUTHENIUM

A. High-energy run

Natural Ru has seven stable isotopes. Table III lists these isotopes together with their abundances and neutron binding energies. Since ^{99}Ru and ^{101}Ru have higher binding energies than the other isotopes, it is rather straightforward to identify the resonances belonging to these two isotopes without ambiguity by the examination of their high-energy decay.

On the other hand, the isotopic identification of resonances belonging to isotopes other than ^{99}Ru and ^{101}Ru will be complicated by the fact that the high-energy transitions from these resonances will occur in that region of the spectrum where the transition density from capture in ^{99}Ru and ^{101}Ru is expected to be high. This is particularly true in the cases where the identification is attempted for those unidentified resonances which are not resolved from the generally much stronger ^{99}Ru and ^{101}Ru resonances.

In the following we discuss new information obtained from the high-energy decay.

1. *10-eV resonance*

The high-energy decay of this resonance indicates clearly that it belongs to ^{99}Ru (see Fig. 2 and Table I). Since the ground state of the target nucleus ^{99}Ru is $\frac{5}{2}^+$, s-wave neutron resonances will have spin-parity of 2^+ or 3^+. This resonance is seen to populate the 4^+ state in ^{100}Ru at 1227 keV.[5] The strength of this transition indicates a dipole rather than a quadrupole character. This implies a J^{π} of 3^+ for this resonance.

2. *15-eV resonance*

Of the isotopically identified resonances only the 15-eV resonance in ^{101}Ru had not been assigned a spin in Refs. 2 and 3. The high-energy decay of this resonance shows a strong transition which populated a state at 1105.7 ± 1.5 keV (see Fig. 3). This indicates decay to the 4^+ level at 1106.1 keV,[7] implying a 3^+ spin for the resonance. However, the 1106.1-keV state is a member of a doublet, the second member being the 2^+ state at 1103.2 keV. Since the γ-ray resolution is not

TABLE II. Partial widths for ^{101}Ru(n,γ) ^{102}Ru.

				^{101}Ru(n,γ)											
				$E_n = 15.7$ eV $J = 3$		$E_n = 42.3$ eV $J = 3$		$E_n = 52.1$ eV $J = 3$		$E_n = 61.8$ eV $J = 2$		$E_n = 66.8$ eV $J = 2$		$E_n = 112.5$ eV $J = 2$	
E (keV)	ΔE (keV)	E_x [a] (keV)	J^{π} [b]	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)
9219.6	2.0	0.3	0^+							0.30	0.17				
8746.1	1.0	473.8	2^+	0.18	0.06	0.27	0.06	0.26	0.26	0.40	0.19	0.15	0.07		
8112.5	1.2	1107.4	4^+	0.90	0.12	0.31	0.08								
7697.1	1.0	1522.8	3^+	0.56	0.07	1.34	0.14	0.33	0.33	0.80	0.23	0.24	0.09	1.67	0.38
7641.8	1.0	1578.1	$(1,2^+)$			0.06	0.09	0.42	0.35	0.24	0.21	0.06	0.08	0.38	0.72
7184.6	1.4	2035.3	2^+	0.18	0.08	0.62	0.15	0.28	0.33						
7174.8	0.5	2045.1	2, 3			5.34	0.22	2.11	0.42						
7029.9	1.0	2190.0	(2)			0.27	0.13	1.00	0.34			0.05	0.11	1.37	0.59
6976.9	1.1	2243.0						1.12	0.38	0.18	0.26				
6957.2	0.3	2262.7	2^+			10.53	0.71	1.70	0.39	2.55	0.34	2.89	0.18	2.39	0.74
6915.2	0.5	2304.7	(2)	0.66	0.13			0.75	0.37						
6849.8	1.0	2370.1				0.42	0.14								
6834.2	0.5	2385.7	2, 3	0.22	0.10					3.75	0.40	0.88	0.14	2.12	0.72
6796.9	2.2	2423.0						0.83	0.37			0.26	0.11		
6751.2	0.5	2468.7	2, 3	0.58	0.12					3.72	0.47	0.37	0.11		
6626.6	0.3	2593.3		2.57	0.16							0.39	0.14	1.68	0.66
6566.7	0.7	2653.2		0.12	0.10	0.62	0.15								
6517.2	0.7	2702.7		0.40	0.12	0.37	0.12					0.21	0.13		
6508.3	1.0	2711.6				0.35	0.12	2.44	0.42			0.57	0.14	2.08	0.75
6428.8	0.4	2791.1				1.73	0.16								
6417.2	1.2	2802.7		1.18	0.16	0.06	0.15	0.36	0.35	1.68	0.36	0.27	0.23		
6397.0	0.5	2822.9						0.61	0.36			0.75	0.14		
6342.4	0.9	2877.5						0.94	0.42	0.88	0.34				
6320.9	1.0	2899.0		0.67	0.17					0.46	0.34			0.48	0.70
6273.8	1.0	2946.1		0.80	0.16	3.93	0.21	0.79	0.46	0.35	0.31				
6263.5	1.4	2956.4						1.28	0.46	1.41	0.34	1.91	0.16	0.79	0.65
6252.9	0.9	2967.0		0.44	0.15	0.24	0.16	0.86	0.46						
6185.8	1.5	3034.1		0.36	0.16			1.49	0.50	0.91	0.32	1.70	0.17		
6163.0	1.0	3056.9						0.46	0.45	2.06	0.26	0.44	0.15		
6134.3	1.5	3085.6						1.31	0.45	0.81	0.31	0.35	0.17		
6062.8	1.8	3157.1				0.56	0.15	0.75	0.43			1.35	0.19		
5985.7	0.6	3234.2				0.36	0.14			1.93	0.35			2.97	0.71
5975.2	1.0	3244.7		0.73	0.14	0.78	0.14	0.91	0.50			0.58	0.15	1.44	0.68
5872.7	2.4	3347.2		0.97	0.14										
5831.3	0.8	3388.6		0.75	0.14										
5769.5	0.6	3450.4										1.16	0.22	1.61	0.79
5751.0	1.2	3468.9		0.83	0.17							0.65	0.15	2.01	0.78
5670.8	1.1	3549.1		0.37	0.13	0.60	0.13					0.30	0.16		
5643.2	1.0	3576.7		0.37	0.15	0.39	0.16							1.41	0.78
5539.8	0.8	3680.1		0.47	0.14					0.31	0.33				
5531.3	0.7	3688.6		0.47	0.14	0.32	0.16								
5520.3	0.8	3699.6		0.23	0.13	0.12	0.14			0.69	0.31				
5501.5	0.5	3718.4		0.62	0.15										
5486.9	2.0	3733.0		0.31	0.15										
5478.6	0.6	3741.3				0.64	0.16								
5470.6	0.8	3749.3				0.50	0.15	1.24	0.44						
5461.4	0.4	3758.5		1.03	0.14	0.16	0.12					0.33	0.16		
5437.8	0.6	3782.1				0.89	0.13							1.62	0.64
5428.6	0.9	3791.3				0.62	0.13								
5398.8	0.6	3821.1		0.28	0.14			0.87	0.46						
5379.0	0.7	3840.9				0.33	0.14								
5344.2	1.3	3875.7		0.48	0.13			0.69	0.41						
5334.3	0.5	3885.6		0.38	0.13	0.24	0.14								
5282.9	0.9	3937.0		0.52	0.14	0.25	0.13							1.76	0.79
5247.0	1.0	3972.9		0.72	0.14	0.18	0.15								

TABLE II *(Continued)*

				^{101}Ru(n,γ)											
				E_n = 15.7 eV J = 3		E_n = 42.3 eV J = 3		E_n = 52.1 eV J = 3		E_n = 61.8 eV J = 2		E_n = 66.8 eV J = 2		E_n = 112.5 eV J = 2	
E (keV)	ΔE (keV)	E_x [a] (keV)	J^π [b]	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)
5186.4	1.0	4033.5		0.37	0.14										
5153.7	0.8	4066.2				0.35	0.14	0.91	0.44						
5138.9	0.8	4081.0						0.81	0.44			0.33	0.15		
5132.0	0.9	4087.9		0.42	0.14										
5106.0	2.0	4113.9						0.90	0.55						
5094.6	1.0	4125.3		0.38	0.13	0.26	0.14								
5040.8	1.1	4179.1				0.18	0.18								
5022.1	0.8	4197.8		0.32	0.16										

[a] E_x based on B_n = 9219.9 ± 0.9 keV.

[b] J^π from Ref. 7 except where discussed in text.

adequate at 8.11 MeV to definitely establish that the high-energy transition populated the 1106.1-keV rather than the 1103.2-keV level, further evidence for the 3$^+$ assignment is necessary. This is obtained from the low-energy run as will be discussed later.

3. 65.66-eV resonance

This unidentified resonance is not resolved from the ^{101}Ru 2$^+$ resonance at 66.8 eV. The spectrum belonging to this TOF peak is dominated by lines belonging to the decay of the 66.8-eV resonance. However, nine primary transitions are observed whose energies match those expected from capture in ^{104}Ru. The energies and relative intensities of these transitions are given in Table IV. The energies of the levels fed by these transitions are also given together with the corresponding level energies of Refs. 9 and 10. While accidental energy matching is possible since these transitions would correspond to decay to states of excitation energies higher than 3.3 MeV in ^{102}Ru, only the 5752-keV γ ray has measurable intensity in two of the five ^{101}Ru resolved resonances (compare with Table II).

The observation of these high-energy transitions coupled with similar evidence from the low-energy run (to be discussed below) lead to ascribing these transitions to capture in the 65.66-eV resonance which is thus assigned to the isotope ^{104}Ru.

As seen in Table IV, transitions populating the 20.5-keV first excited state and the state at 159 keV in ^{105}Ru are observed. The ln = 2 20.5-keV state is assigned a $\frac{5}{2}^+$ spin based on the (d,p) spectroscopic strength,[10] while the ln = 0 159-keV state[10] has a spin $\frac{1}{2}^+$ since the ground state of the

TABLE III. Abundance and neutron separation energy for Ru isotopes.

Mass No.	Abundance (%)	S_n (keV) [a]	S_n (from n,γ) [b]
96	5.51	8040 ± 100	
98	1.87	7468 ± 5	
99	12.72	9673.5 ± 1.0	9673.2 ± 0.7 [c]
100	12.62	6805 ± 4	
101	17.07	9216.1 ± 1.9	9220.4 ± 0.9 [c]
102	31.61	6225 ± 6	6232.4 [d]
104	18.58	5908 ± 8	5910.4 [d]

[a] Reference 20.

[b] Corrected for recoil.

[c] Values obtained in this experiment.

[d] From Refs. 8 and 9.

TABLE IV. Transitions corresponding to decay of ^{105}Ru observed in the 67-eV neutron TOF peak.

					Thermal (n,γ) [a]		(d,p) [b]
E_γ (keV)	ΔE (keV)	E_x (keV)	I	ΔI	E_x (keV)	J^π	E_x (keV) [c]
5910.5	1.5	0	9	4	0	$\frac{3}{2}^+$	
5888.3	1.0	22.2	20	4	20.5	$(\frac{5}{2}^+)$	20.5
5752.4	0.7	158.1	19	5	159.0	$(\frac{3}{2},\frac{5}{2},\frac{7}{2})$	160.5
5589.3	0.8	321.2	12	4	321.5	$\frac{3}{2}$	322.5
5448.0	2.0	462.5	7	5	464.3	$(\frac{1}{2},\frac{3}{2})$	465.5
5324.7	1.2	585.8	7	5	582.6		578.5
5149.2	1.3	761.3	8	4			758.5
5114.5	1.0	796.0	10	4	794.7	$(\frac{1}{2},\frac{3}{2})$	
5087.0	1.3	823.5	9	5			824.5
4175.6	1.2	1734.9	17	8	1734.3	$(\frac{1}{2},\frac{3}{2})$	

[a] From Ref. 9.

[b] From Ref. 10.

[c] Energy shifted by 20.5 keV as pointed out by Hratsnik *et al.* (Ref. 9).

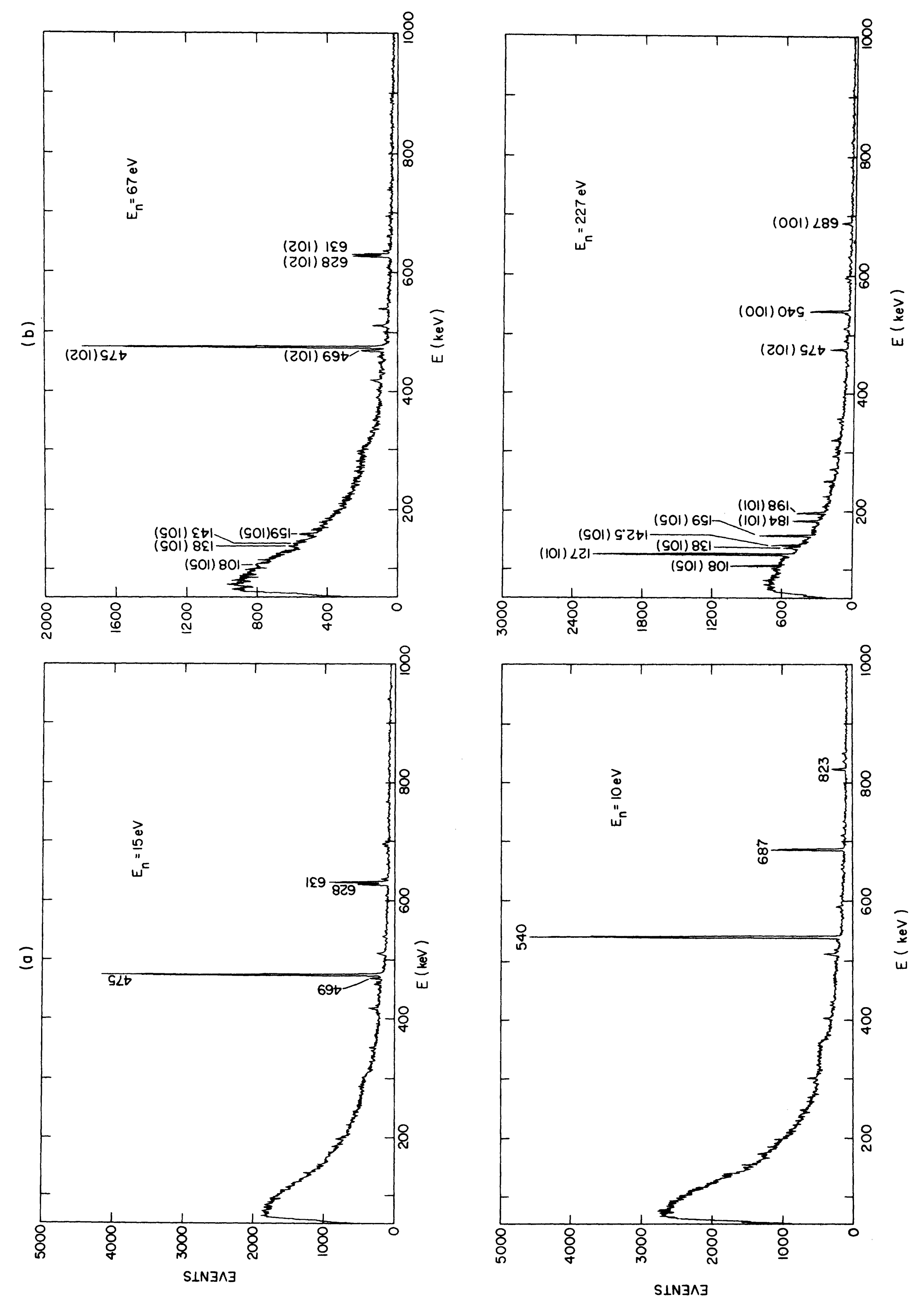

FIG. 4. The low-energy γ-ray spectra from four ruthenium resonances: (a) The 10-eV ^{99}Ru and 15-eV ^{101}Ru resonances; (b) The 67- and 227-eV mixed peaks.

even-even ^{104}Ru nucleus is 0^+. Thus, assuming dipole character for the high-energy transitions feeding these two states leads to a spin $\frac{3}{2}$ for the capturing state, which would imply a p-wave character for the resonance. Thus the spin-parity for this resonance is $\frac{3}{2}^-$. Since the $\frac{3}{2}^-$ assignment of the resonance is based solely on the 20.5-keV level being a $\frac{5}{2}^+$ state, it should be viewed as tentative.

4. *Other resonances*

The high-energy decay of the other resonances is consistent in all cases with the isotopic and spin assignments given in Refs. 2 and 3. No further information could be obtained on the other unidentified resonances.

B. Low-energy run

The spectra obtained for four TOF peaks in the low-energy run are shown in Figs. 4(a) and 4(b). These are the TOF peaks at 10, 15, 67, and 227 eV. The 10-eV spectrum [Fig. 4(a)] shows typical decay of the ^{99}Ru resonances. The prominent peaks are associated with transitions from the low-lying 2^+ and 4^+ states of ^{100}Ru. This confirms the isotopic assignment of this resonance based on high-energy decay. The 15-eV spectrum shows the low-energy decay of the ^{101}Ru resonances. Of particular importance is the doublet at 628 and 631 keV which corresponds to the decay of the 1103, 1106 doublet to the first excited state at 475 keV in ^{102}Ru. The 67-eV low-energy spectrum is also seen to be dominated by transitions in ^{102}Ru (compare with spectrum of 15 eV). However, the lines at 108, 138, 143, and particularly 159 keV, which are weakly observed in this spectrum, are among the strongest low-energy lines reported by Hratsnik *et al.*[9] These lines, which are absent in the 15-eV spectrum, are seen strongly in the 227-eV spectrum where a ^{104}Ru resonance contributes to the capture. This constitutes a strong confirmation that the unassigned resonance at 65.66 eV belongs to ^{104}Ru, and supports the conclusion drawn from the high-energy γ-ray data. In addition to the transitions in ^{105}Ru mentioned above, strong transitions belonging to ^{100}Ru, ^{101}Ru, and ^{102}Ru are also seen in the spectrum of the TOF peak at 227 eV.

As pointed out by Huizenga and Vandenbosch[21] the relative population of low-lying states of different spins can be utilized in obtaining the spins of the capturing states. The relative intensities of the two transitions proceeding to the first 2^+ state from the second 2^+ and first 4^+ states were used in this experiment for this purpose. The ratio $R = I(2^+ \rightarrow 2^+)/I(4^+ \rightarrow 2^+)$ is expected to be smaller for spin-3 resonances than for spin 2-resonances. This follows from noting that the number of cascades feeding the two states depends upon the spin of the initial state.

Plots for the relative-intensity ratio R are presented for ^{99}Ru and ^{101}Ru resonances in Fig. 5(a) and Fig. 5(b), respectively. The separation of the resonances into two separate groups is clearly seen. The 10- and 15-eV resonances are both seen to fall with the spin-3 groups in their respective plots. This confirms the spin assignments for these resonances based on high-energy decay. The spins of the other resonances are seen to be in agreement with those of Refs. 2 and 3.

V. LOW-LYING STATES OF THE PRODUCT NUCLIDES

A. ^{99}Ru$(n,\gamma)^{100}$Ru

85 transitions with $E_\gamma > 4$ MeV were observed in capture in ^{99}Ru resonances. 30 of these transitions are not observed in thermal capture[15] nor do they populate low-lying states that are known from β-decay studies.[5] 16 of the states of Ref. 5 are seen to be fed by primary transitions. Assuming that transitions of energy higher than 5 MeV are all primary transitions, the excitation energy of

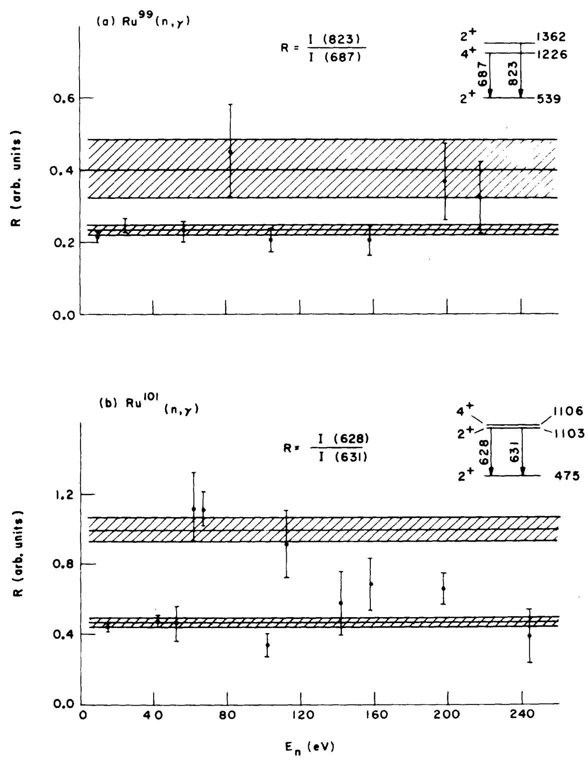

FIG. 5. Experimental intensity ratios for γ rays depopulating low-lying states in ^{100}Ru and ^{102}Ru.

levels that are fed by these transitions was calculated and included together with the γ-ray transition energies and partial radiation widths in Table I. The level scheme is shown in Fig. 6 and is compared to the level diagram of Berzins, Bunker, and Starner,[5] obtained from β-decay studies.

The spins of the low-lying states cannot be determined uniquely from high-energy transitions. However, in certain cases where the transition strength justifies the assumption of dipole radiation, it is possible to limit the spins given by the β-decay study to a unique value. This is particularly applicable in this case, to levels given a spin of (1, 2) by the β-decay study. In the following we discuss the spins obtained from combining the results of this experiment with those of the β-decay study of Ref. 5.

1. Levels at 2097.8 and 2168.2 keV. These are given as 1^-, 2^- in Ref. 5. Both are fed by transitions from the 3^+ resonances at 10, 25, and 57 eV. The assumption that no $M2$ transitions are observable with our sensitivity rules out the 1^- assignment. Therefore these two levels are assigned as 2^-.

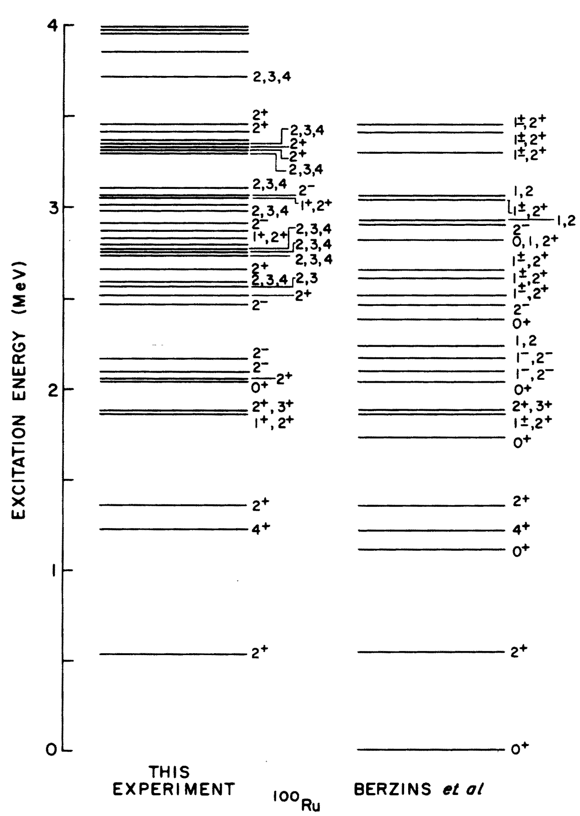

FIG. 6. The level scheme for ^{100}Ru. Spin assignments and levels derived from the present experiment are compared to previous results.

2. Levels at 2514.6, 3325.9, 3419.8, and 3466.4 keV. These are reported as $1^{\pm}$, 2^+ in Ref. 5. Each of these levels is seen to be fed by at least one 3^+ resonance with a strength which justifies a dipole character for the transition. This leads to the assignment of 2^+ for all of these levels. (The level at 3419.8, which is not listed in Table I, is fed strongly from the 3^+ resonance at 104 eV, and appears in our experiment in the unresolved peak near 100 eV.)

3. Level at 3070.4 keV. This level is given as 1, 2 in Ref. 5. It is seen to be fed strongly by the resonances at 10, 25, and 82 eV. This leads to a spin of 2. The reduced $E1$ strength, as defined in Sec. VI below, for the transitions feeding this level from the 10- and 25-eV resonances are 4.2×10^{-9} and 5.3×10^{-9} MeV^{-3}, respectively. When compared to Bartholomew's estimate[22] for average $E1$ reduced strength of 3×10^{-9} MeV^{-3}, these transitions imply $E1$ character leading to a negative-parity assignment for this level. However, since highly enhanced $M1$ transitions are observed in this experiment, as will be discussed in Sec. VI below, this parity assignment is considered tentative.

4. Levels at 1866.7 and 3058.1 keV. These are given as $1^{\pm}$, 2^+ in Ref. 5. These states are fed by transitions from 3^+ resonances ruling out spins of 1^-. The transitions are not strong enough to exclude the possibility of $E2$ radiation. Thus these levels are given as 1^+, 2^+.

B. ^{101}Ru$(n,\gamma)^{102}$Ru

86 transitions with $E_\gamma > 4$ MeV were observed in capture in ^{101}Ru resonances. 39 of these are not observed in thermal capture[15] and do not populate states known from β decay as given in Ref. 7. Seven of the levels determined from β decay are seen to be populated by primary transitions. Table II lists the energies and partial widths for transitions with $E_\gamma > 5$ MeV. The excitation energies and known spins of levels populated by these transitions are also listed. Figure 7 compares the levels seen in the present experiment with those observed by Konijn *et al.* from β decay.

The spins of some low-lying states in ^{102}Ru can be obtained from the combination of high-energy-decay and β-decay results in a similar way as discussed above for levels of ^{100}Ru. These arguments would be useful for only two levels suggested by the β-decay work. These are the levels at 1580.6 and 2261.2 keV which are given as $(1, 2^+)$ and $(1^+, 2^+)$, respectively, in Ref. 7. The strength of the transitions to the 1580.6 does not allow a definite spin or parity assignment for this level. On the other hand, the 2261.2-keV level is populated strongly from the 3^+ 42-eV resonance indicating a spin of 2^+ for this level.

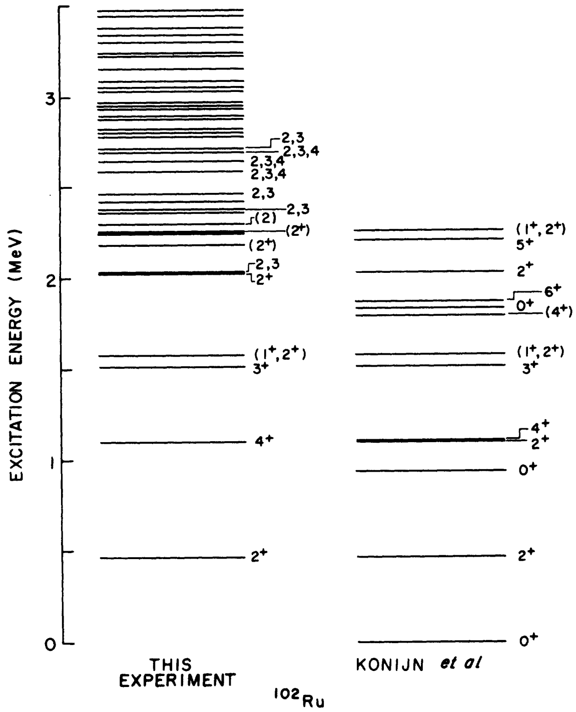

FIG. 7. The level scheme for ^{102}Ru.

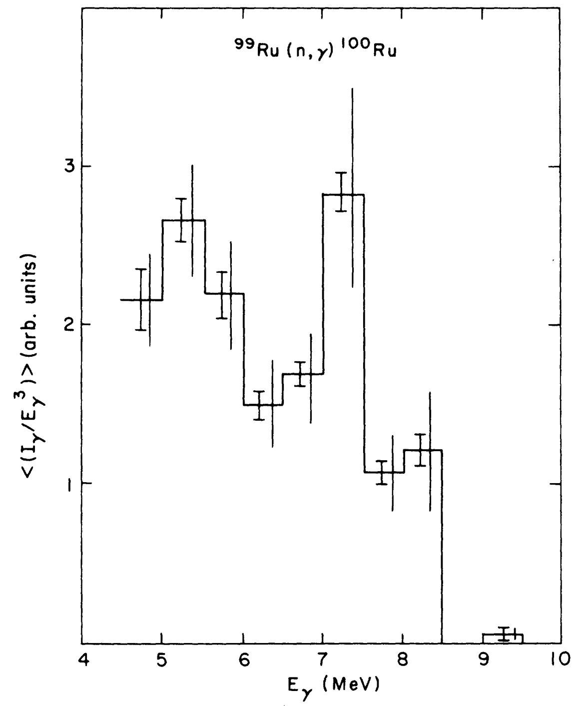

FIG. 8. Plot of reduced γ-ray intensities, averaged over 500-keV intervals in energy, for ^{100}Ru. The open ended error bars denote rms sampling errors, while the closed bars indicate measurement errors.

VI. DISCUSSION AND RESULTS

A. Statistical properties

Most of the low-lying states are positive parity in both ^{100}Ru and ^{102}Ru. Since s-wave capture in ^{99}Ru and ^{101}Ru leads to positive-parity states, the transitions to low-lying states are predominantly $M1$. The distribution and correlations of these transitions were studied. The widths were found to follow a χ^2 distribution consistent with the Porter-Thomas[23] distribution. A ν value of $0.93^{+0.57}_{-0.33}$ was obtained for transitions in ^{100}Ru for 3 spin-3 resonances and 18 final states. The distribution for transitions in ^{102}Ru for 3 spin-3 resonances and 16 final states was found to follow a χ^2 distribution with a ν value of $0.98^{+0.50}_{-0.33}$. These values were obtained using the maximum-likelihood method utilizing a Monte Carlo program for calculating the probability that the ν value for a sample similar to that of the experimental widths but drawn from a population with ν value ν_0, has a ν value higher than that of the experimental sample. The errors are based on the 10 and 90% limits.

The average correlation coefficients for neutron reduced widths and radiation widths were found to be consistent with zero. Also, no significant average correlation was obtained for the radiation widths populating different states.

B. Transition strength distribution and $M1$ strength function

1. ^{100}Ru

Figure 8 shows the reduced transition strength $\langle I_{\gamma if}/E_\gamma{}^3\rangle$ for ^{100}Ru averaged over energy regions of 0.5 MeV. The error bars are based on statistical errors, while the error lines indicate the uncertainty due to Porter-Thomas fluctuations. As seen in the figure, a concentration of strength is apparent for transitions with energy between 7.0 and 7.5 MeV. Five transitions are included within this region, two of which are $M1$, one is $E1$, and two populate states of unknown parity. Known $M1$ and $E1$ transitions contribute about equally to the sum with both contributions amounting to about one half of the total strength. Thus, we cannot definitely attribute this structure to a given multiple order.

There are nine final states in ^{100}Ru which are given a definite positive-parity assignment.[5] The $M1$ radiation-strength function defined as[22]

$$\bar{k}_{M1} = \langle \Gamma_{\gamma if}(\mathrm{obs})/E_\gamma{}^3 D\rangle$$

was calculated for transitions feeding these states from the three resolved 3^+ resonances. The value of D, the average spacing of spin-3 capturing states, was taken from Ref. 3. A value of $(20\pm6)\times10^{-9}$ MeV^{-3} was obtained for $\bar{k}_{M1}$. (The uncertainties in strength functions include uncertainties due to limited sample size and statistical errors but do do not include the uncertainties due to normalizations nor the uncertainties in the average level spacing D.) This indicates enhancement of $M1$ strength when compared to the estimate of Bartholomew,[22] who gives $k_{M1}\approx4\times10^{-9}$ MeV^{-3} but is in agreement with the recent estimate by Bollinger[24] who observes that for most nuclides in this mass region a value of 18×10^{-9} MeV^{-3} is obtained.

Four states are identified as negative-parity states in the β-decay study.[5] The $E1$ radiation-strength function defined by[22]

$$k_{E1}=\langle \Gamma_{\gamma if}(\text{obs})/A^{2/3}E_\gamma{}^3D\rangle$$

was found for transitions to these states to be $(0.9\pm0.4)\times10^{-9}$ MeV^{-3}. Bartholomew's estimate[22] for this function is 3×10^{-9} MeV^{-3}, while a value of 1.2 $\times10^{-9}$ MeV^{-3} is obtained from the more recent estimate of Bollinger.[24]

2. ^{102}Ru

The reduced strength for ^{102}Ru is shown in Fig. 9. As in ^{100}Ru, a concentration of strength is suggested for transitions between 6.5 and 7.0 MeV. This region includes 11 transitions. The γ ray of energy 6.957 MeV populates the 2^+ state at 2261 keV and then is of $M1$ character. This transition contributes 0.43 of the peak. Thus in this case we can attribute the enhancement to $M1$ transitions.

Five final states are known which are fed by $M1$

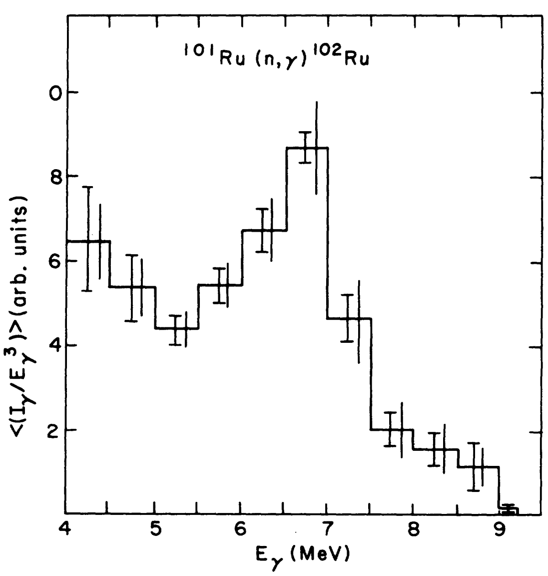

FIG. 9. Reduced intensity plot for ^{102}Ru.

transitions from the capturing resonances. The photon $M1$ strength function $\bar{k}_{M1}$ for these transitions is $(53\pm14)\times10^{-9}$ MeV^{-3} which indicates considerably enhanced $M1$ transition rates. A value of $(204\pm119)\times10^{-9}$ MeV^{-3} is obtained from six resonances considering the 6.957-MeV transition alone. If one excludes the 6.957-MeV transition a value of $\bar{k}_{M1}=(15\pm5)\times10^{-9}$ MeV^{-3} is obtained, which still indicates enhancement when compared to the estimate of Bartholomew, but not when compared to the estimate of Bollinger.

The anomaly of 6.957-MeV transition is so large that it warrants further examination. The different possibilities that may lead to such large apparent strength functions are discussed in the following:

a. The transition is E1 and not M1. This transition populates the state at 2261.2 keV which is given as 1^+, 2^+ by Konijn *et al.*[7] The decay of this state[6,7] shows six transitions, one to the 0^+ ground state and the rest to states of spin 2^+ or 3^+.

Assuming an $E1$ primary transition leads to a spin-parity of 2^- for the 2261-keV level. The ground-state transition is then an $M2$ transition competing with the other five transitions which will be $E1$ in this case. This assumption would lead to the conclusion of largely enhanced $M2$ transition rate which is difficult to justify.

b. The 2261-keV level is a doublet of opposite parities. Under this assumption the primary transition proceeds to the negative-parity state as $E1$, while the transition to the ground state proceeds from the positive-parity member of the doublet. This implies that the positive member is the one populated in β decay. We see no evidence to support such an assumption either from high-energy or from low-energy decay. We have no proof, however, to definitely rule out this possibility.

In any event, the random summing of such transitions would *not* be expected to produce a strength concentration such as that in evidence in Fig. 9, since this figure represents summed transitions strengths over 0.5-MeV intervals.

c. The enhancement is a result of Porter-Thomas fluctuations of partial widths. This assumption is tested by calculating the ratio k_{M1}(observed)/k_{M1}(average) and determining the probability of obtaining such a value for a χ^2 distribution with the appropriate number of degrees of freedom. This ratio is ~11 for the transition to the 2261-keV level. A factor of 11 is inadmissibly large for a set of six resonances. This shows that the statistical fluctuation assumption is not sufficient to explain such a large enhancement.

We are thus led to the conclusion that there is an anomaly in the radiation strength from these two nuclides near 7 MeV. This anomaly is most plausibly associated with the $M1$ radiation component. An explanation for large $M1$ strength that has been suggested is the $M1$ giant resonance involving a spin-flip mechanism.[25] In this case the $g_{7/2} \to g_{9/2}$ transition seems to be the transition involved.

The $\frac{5}{2}^+$ ground state of ^{101}Ru with 44 protons and 57 neutrons may be described by a shell-model configuration of the form

$$\left\{ [a_1(p_{1/2})^2(g_{9/2})^4 + a_2(g_{9/2})^6]^{\pi}_{0^+} + \left[\sum_i b_i (s_{1/2})^{k_i} (g_{7/2})^{l_i} (d_{5/2})^{m_i} (d_{3/2})^{n_i} \right]^{\nu}_{5/2^+} \right\},$$

where the sum is over all possible combinations that produce the proper spin and satisfy the condition that $k_i + l_i + m_i + n_i = 7$. From this description one sees that a spin-flip transition involving the $g_{7/2} \to g_{9/2}$ orbitals has to be preceded by lifting a neutron or a proton from a $g_{9/2}$ to a $g_{7/2}$ orbital. Therefore the spin-flip transition must involve at least a two-step process (doorway state) rather than a single-step process (single-particle decay).

The lack of significant single-particle component to the radiation process for this transition is further implied by the absence of a significant correlation between the reduced neutron widths and the partial radiation widths. A correlation coefficient of 0.22 was obtained in this case, which is consistent with zero correlation for the sample size considered. The above conclusions are in agreement with theoretical predictions where $M1$ single-particle transitions are forbidden for s-wave particle capture and the two-step process is the simplest mode of $M1$ radiative capture of such a particle.[26]

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