Gamma-Ray Spectra from Radiative Capture of Thermal and Resonance Neutrons in Mercury and Tungsten*

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A 20-cc lithium-drifted germanium detector has been used in conjunction with the R.P.I. Electron Linac Neutron Velocity Selector to examine the high-energy gamma-ray spectra arising from thermal and resonance neutron capture in mercury, and from resonance capture in tungsten. The effective gamma-ray energy resolution of 12–18 keV allowed 29 transitions to be examined in the energy range 4.67 to 8.02 MeV following capture of thermal neutrons and resonance neutrons of energy 34, 130, and 175 eV in ^{199}Hg (116 transitions in all). The spectra are interpreted in terms of levels in the compound nucleus ^{200}Hg. An analysis of the strengths of 88 $E1$ transitions indicates a Porter-Thomas distribution, the best fit being achieved with a χ^2 function with $0.96_{-0.17}^{+0.24}$ degrees of freedom. The mean reduced partial radiation width for transitions to states in ^{200}Hg above the pairing energy gap is shown to be significantly higher than the corresponding mean width for transitions to collective states below the pairing energy. No such effect is obvious in the case of resonance capture in ^{183}W. A comparison between resonance capture in ^{198}Hg and ^{182}W, where no pairing energy gap exists, shows that the mean partial radiation width is a factor 4 larger for ^{198}Hg than for the highly distorted ^{182}W.

1. INTRODUCTION

THE advent of the lithium-drifted germanium detector as a high-energy high-resolution gamma-ray spectrometer of moderate efficiency has made possible the study of the excitation of complex nuclear level schemes in many experiments where previously only a few levels or groups of levels could be resolved. This paper describes the application of the technique to the study of the high-energy gamma-ray spectra following resonance neutron capture in heavy elements. Previously, because of efficiency considerations, such measurements[1] have been made with sodium-iodide detectors which gave energy resolutions of, at best, around 200 keV so that for heavy elements only transitions to a few levels could be obtained under favorable circumstances. With germanium detectors, a useful efficiency combined with a resolution of better than 20 keV is easily achieved in this type of experiment[2–5] so that transitions to many levels can be observed in most cases. In fact, this resolution is comparable with the best obtained in the past in thermal capture gamma-ray studies with magnetic spectrometers, so that it has now become possible to observe in detail the fluctuations in the spectra from resonance to resonance and the effect of changes in the angular momentum of the capturing state, and to obtain significant values for mean transition strengths for comparison with nuclear models.

2. EXPERIMENT

Figure 1 shows the general arrangement of the experiment. Pulses of photoneutrons from the tantalum target of the electron linac were moderated in a polyethylene slab. Moderated neutrons passed through a cadmium filter and were collimated on to the capture sample which was situated 12 m from the neutron source. Capture gamma rays from the sample were detected in the germanium spectrometer, the energy of the captured neutron being deduced from the time of flight over the 12 m separating source and sample. Of particular importance in this experiment was the position of the photoneutron target which was well shielded, so that the primary radiation (gamma-flash) could not reach the capturing sample directly. This prevented overloading of the amplifier during the accelerator pulse, which would otherwise have adversely affected the resolution of the gamma-ray spectrometer.

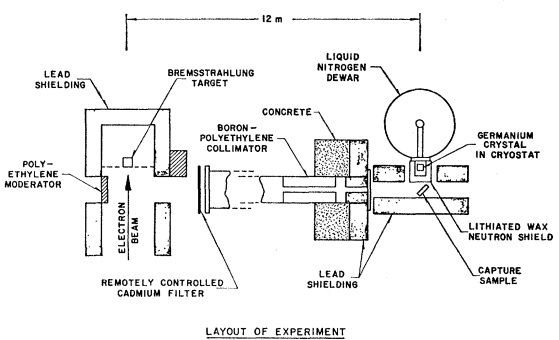

FIG. 1. Layout of experiment.

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[1] L. M. Bollinger, R. E. Coté, R. T. Carpenter, and J. P. Marion, Phys. Rev. **132**, 1640 (1963).

[2] H. E. Jackson (private communication to J. Julien); and in *Proceedings of the Antwerp Conference on the Study of Nuclear Structure with Neutrons, 1965*, edited by M. Neve, P. Van Assche, and J. Vervier (North Holland Publishing Company, Amsterdam, 1966), p. 169.

[3] A. Bloch, H. E. Jackson, and C. Samour, Bull. Am. Phys. Soc., **11**, 336 (1966).

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[5] K. T. Faler, R. R. Spencer, and D. R. Dixon, Bull. Am. Phys. Soc., **11**, 336 (1966).

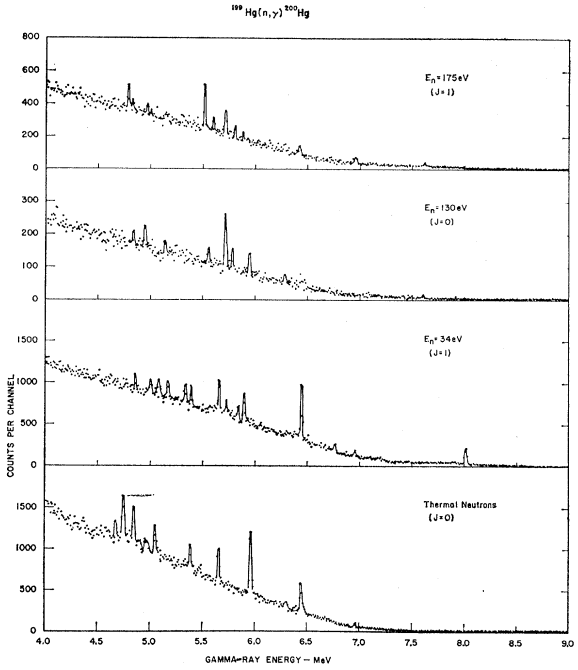

FIG. 2. Gamma-ray spectra for reaction ^{199}Hg$(n,\gamma)^{200}$Hg.

The 20-cc coaxially drifted germanium detector[6] used in the experiment had a linewidth of better than 4 keV for the 660-keV gamma ray from ^{137}Cs with electronics optimized for high resolution. When used with the time-of-flight system, certain compromises had to be made which increased the optimum linewidth in the energy range 4.5 to 10 MeV to 12 keV. Pulse overlap due to high instantaneous count rates broadened the lines further in some cases, but in the work reported here, the gamma-ray energy resolution was never worse than 18 keV. The crystal pulses were amplified and passed through 200 ft of 93-Ω double-screened coaxial cable to the PDP-7 computer-analyzer system. Here the pulse-height and time-of-flight information were separately encoded, then accepted by the computer and stored in the appropriate memory cell.

The computer program under which the data were stored could provide up to 25 adjustable time-of-flight groups each with 256 pulse-height channels. For the present experiment the program was used to accept 6 time-of-flight groups, each with 1024 amplitude channels (5 resonances+background) for the mercury measurements, and 12 time-of-flight groups each with 512 amplitude channels for tungsten. The data were continuously displayed on a storage oscilloscope during accumulation, and during each run the accumulated data were punched out on paper tape at intervals of 3 h lest any drifting should occur.

Pulse-height–versus–time-of-flight runs were made on a rectangular slab of mercuric oxide having a superficial density of 3.1 g/cm^2 and on a metallic sample of tungsten (6.0 g/cm^2). Thermal spectra (Cd filter removed) were also obtained for these samples and for a metallic sample of iron (4.0 g/cm^2). The thermal spectra were used for gamma-ray energy calibration purposes. All samples were natural isotopic mixtures and were placed at 45° to the neutron beam.

The spectra observed for ^{199}Hg in the energy range from 4 MeV upwards are shown in Fig. 2. The energy scale is based primarily on the thermal measurements on iron by Groshev *et al.*,[7] but this calibration is in excellent agreement with the thermal measurements of Kinsey and Bartholomew[8] on mercury and tungsten.

3. DATA REDUCTION

The pulse-height spectra, after subtraction of a background term, were normalized to the γ-ray yield at 2 MeV. This point of the spectrum was chosen since it gave the best cross calibration between the intensities of the high-energy transitions observed in the three thermal spectra (Hg, W, and Fe), and the published data of Groshev and Kinsey.[7,8] The background correction was very small for the thermal spectra (0.25% for mercury), and for the resonances it varied between 9% and 25%. The positions and areas under the main peaks observed were then recorded. If peaks appeared in more than one spectrum which were within ± 1 channel width (8.6 keV) of each other, they were recorded as the same transition. If separated by 2 or more channels, they were recorded as separate transitions. In fact, one such pair was found to be separated by 3 channels and another by 3.5. All other pairs had considerably larger spacings and were clearly distinguished from coincident pairs. The areas under the peaks were corrected for the logarithmic variation of the pair creation cross section of germanium with the photon energy[9,10] (the total photon cross section being nearly constant from 4 to 10 MeV), and all were normalized to the area under the 5.95-MeV line in the thermal spectrum of mercury which was taken to occur in 12% of all captures of thermal neutrons as recorded by Kinsey and by Ad'yasevich *et al.*[11] The energies and intensities of the transitions observed, using these ground rules, are listed in Table I, together with the results of other authors.

[6] Princeton Gamma Tech Model IG40ED.

[7] L. V. Groshev, A. M. Demidov, G. A. Kotelnikov, and V. N. Lutsenko, Nucl. Phys. **58**, 465 (1964).

[8] B. B. Kinsey and G. A. Bartholomew, Can. J. Phys. **31**, 1051 (1953).

[9] Monte Carlo calculations by Faria and Levesque (Ref. 10) have shown that although edge effects play an important part in determining the variation of efficiency with energy for planar drifted crsytals of 5-mm depletion depth, these effects are very small for a depletion depth of 10 mm. For our coaxially drifted crystal, the effective sensitive depth exceeded 10 mm, and so these effects were ignored.

[10] N. V. de C. Faria and R. J. A. Levesque, IEEE Trans. Nucl. Sci. **NS-13**, No. 3, 363 (1966).

[11] B. P. Ad'yasevich, L. V. Groshev, and A. M. Demidov, in *Conference of the Academy of Sciences of USSR on Peaceful Uses of Atomic Energy, Session of Division of Physical and Mathematical Sciences* (Consultants Bureau, Inc., New York, 1955), p. 195.

TABLE I. Strengths of transition in reaction $^{199}Hg(n,\gamma)^{200}Hg$ expressed as number of transitions per hundred captures.

				Transitions per hundred captures																	
				Thermal neutrons ($J=0$)					130-eV resonance ($J=0$)			34-eV resonance ($J=1$)					175-eV resonance ($J=1$)				
		Energy of final		This work		Ref. 11	Ref. 8	Ref. 13	This work		Ref. 13	This work		Ref. 13	Ref. 1		This work		Ref. 13	Ref. 1	
No.	E_γ[a] (keV)	state (keV)	J^π	I_γ (%)	ΔI_γ[b]	I_γ (%)	I_γ (%)	I_γ (%)	I_γ (%)	ΔI_γ[b]	I_γ (%)	I_γ (%)	ΔI_γ[b]	I_γ (%)	I_γ (%)	ΔI_γ	I_γ (%)	ΔI_γ[b]	I_γ (%)	I_γ (%)	ΔI_γ
1	4665	3358	1+	2.6	0.6	3.5	2		1.4	1.4		0.8	0.7				0.3	0.9			
2	4734	3289	1+	10.2	0.6	6	4		1.9	1.4		0	0.7				0.9	1.1			
3	4788	3235	1+	1.7	0.6				0.3	1.4		0.6	0.7				5.8	1.0			
4	4833	3190	1+	6.8	0.6	10	3		4.0	1.3		2.8	0.7				3.1	1.0			
5	4953	3070	1+	3.9	0.6	3	1		6.8	1.3		1.3	0.7				1.6	1.0			
6	4991	3032	0+, 2+	−0.3	0.6				0.4	1.3		3.8	0.7				1.3	1.0			
7	5043	2980	1+	5.6	0.6	6	3		−0.8	1.2		2.1	0.7				0.1	1.0			
8	5079	2944	0+, 2+	0.4	0.6				−0.6	1.2		3.9	0.7				1.1	0.8			
9	5137	2886	1+	0	0.5				3.7	1.3		0.5	0.7				1.1	0.8			
10	5162	2861	0+, 2+	0	0.5				−0.2	1.1		4.1	0.7				1.5	0.8			
11	5320	2703	1+	0.7	0.5	1.4			−0.4	1.1		4.3	0.6				1.3	0.6			
12	5374	2649	1+	3.2	0.4	4.5	3		1.4	1.1		3.3	0.6				1.4	0.7			
13	5468	2555	1+, 1−	1.2	0.4				0.3	1.1		0.2	0.6				0	0.6			
14	5519	2504	0+, 2+	−0.1	0.4				0.2	1.0		0.1	0.6				10.6	0.7			
15	5549	2474	1+	0.5	0.3				4.0	1.0		1.1	0.6				1.2	0.6			
16	5605	2418	0+, 2+	0	0.3				0.7	1.0		1.5	0.6				2.8	0.6			
17	5646	2377	1+	5.5	0.4	6.7	5		0.8	1.0		7.7	0.6				0.6	0.6			
18	5720	2303	1+	0	0.3				13.8	1.2		3.2	0.5				5.4	0.6			
19	5789	2234	1+	−0.1	0.3				5.0	1.0		0.5	0.5				0.3	0.5			
20	5830	2193	0+, 2+	0	0.3				0	1.0		3.2	0.5				2.1	0.5			
21	5892	2131	1+	0.6	0.3	2			0.5	1.0		5.5	0.5				1.0	0.5			
22	5954	2069	1+	12.0	0.4	10	12	10	6.1	1.0	3.8	0.3	0.4	<0.4			−0.2	0.5	≈1		
23	6295	1728	1+	0.5	0.3	2.4			2.0	0.9		0.2	0.4				1.2	0.4			
24	6450	1573	1+; 0+, 2+	5.1	0.4	4.5	5	4.9	1.0	0.5	2.4	12.0	0.4	10.6			2.0	0.4	2.7		
25	6768	1255	2+	−0.1	0.2			<0.08	−0.6	0.5	<0.06	1.7	0.3	1.0	0.85	0.06	0.1	0.4	<0.07	0.10	0.17
26	6994	1029	0+	0	0.1			<0.1	0	0.3	<0.15	0.3	0.3	<0.52	−0.07	0.05	1.4	0.3	1.0	1.19	0.19
27	7655	368	2+	0.1	0.06	0.1		0.07	0.3	0.2	<0.17	0	0.1	0.17	0.17	0.06	0.6	0.2	1.1	1.08	0.08
28	8023		0+	0	0.05			0.03	0.3	0.2		2.8	0.2	2.9	2.8	0.04	0.1	0.1	0.13	0.12	0.03

[a] Energy measurements listed in column 2 have a basic uncertainty of $\pm\frac{1}{2}$ channel width, or ±4.3 keV. Added to this is the calibration error which is ±4 keV at 7.6 MeV, rising to ±6 keV at 4.4 MeV. The combined uncertainty is thus ±5.6 keV at 7.6 MeV, increasing to ±7.6 keV at 4.4 MeV.

[b] Uncertainties on strengths (ΔI_γ) quoted in columns 6, 11, 14, and 19 are purely statistical errors on the areas. In addition there are errors of a systematic nature associated with the calibration and with the neglect of edge effects in the detector. These are difficult to estimate quantitatively but are probably of the order of ±10% of I_γ. They are thus most important in the case of strong transitions. Bremsstrahlung loss in the detector was not considered.

4. RESULTS

A. ^{199}Hg$(n,\gamma)^{200}$Hg

a. General

The nucleus ^{199}Hg has spin and parity $\frac{1}{2}^-$, giving compound states of 0^- and 1^- for the capture of s-wave neutrons. Neutrons of thermal and 130-eV energy are captured into 0^- states and the resonances at 34 and 175 eV form 1^- states. In the interpretation of the data it is assumed that all of the observed sharp lines correspond to primary transitions from the capturing states. Secondary transitions would be very much weaker and would have an energy spacing corresponding to the level density in the compound nucleus 1 or 2 MeV below the capturing state. They would thus not be individually resolved, but rather would contribute a fluctuating background on which the primary lines are superimposed. Following this reasoning, column 3 of Table I lists the energies of the final states in ^{200}Hg which are populated directly by the observed high-energy transitions.

The strengths of the outstanding transitions in the thermal spectrum agree fairly well with those of Ad'yasevich *et al.* (column 7) and also with those of Kinsey and Bartholomew (column 8) for the higher-energy transitions (as listed in Groshev's Atlas).[12] It should be noted that both of these sets of authors used magnetic spectrometers with resolutions $\gtrsim$100 keV, so that the assignment of strengths to close overlapping lines was difficult.

The resonance results for the first few excited states of ^{200}Hg are in fair agreement with those of Segel *et al.*[13] (columns 9, 12, 15, and 20), who used sodium iodide spectrometers in a coincidence arrangement, and also with the data of Bollinger *et al.*[1] for the 34- and 175-eV resonances (columns 16 and 21), if the latter are normalized to 2.8% for the ground-state transition from the 34-eV resonance.

Segel's coincidence measurements indicate that the state at 1573 keV is a doublet, and our results show that the separation of the two states must be less than our linewidth of 15 keV. This suggests that the states involved may be those at 1570 and 1572 keV reported by Maier *et al.*[14] from a study of the low-energy thermal capture spectrum of mercury, using a diffraction spectrometer.

b. Character of the Levels

The ground state of ^{200}Hg is of 0^+ character, the first excited state at 368 keV is a 2^+ collective state, and the states at 1029 and 1255 keV are the 0^+ and 2^+ members of a collective triplet. The 4^+ member, at 948 keV, is not observed in this experiment, since the transitions involved are of $E3$ or $M4$ type. The doublet at 1573 keV must probably have assignments 1^+ and $(0^+,2^+)$, since transitions to one of the levels are extremely weak from the two 0^- capturing states.[13] The 1^+ level probably represents the onset of particle excitation. We have used the same criterion in deciding on the character of the remaining states; i.e., where a significant ($E1$) transition is observed from either of the 0^- capturing states, we assume the state to be in general 1^+; otherwise an assignment of 0^+, 2^+ is made. There is also a finite probability that some of the transitions observed are of $M1$ character, for example, transition No. 13. This is the weakest transition positively identified and has a strength which is 3 times its standard error. This strength is 0.36 times the mean strength of $E1$ transitions in the thermal spectrum. If we take this as representative of the threshold of detection for the thermal spectrum, then since $M1$ strengths are on average a factor 10 less than $E1$, an $M1$ transition, to be observed, would have a strength greater than 3.6 times the $M1$ mean strength. The probability of this, for a Porter-Thomas[15] distribution,[16] is $\sim$6%. The probability of detecting an $M1$ transition in any of the resonance spectra is at least an order of magnitude smaller, since the poorer statistical error in these cases would demand transitions of ten times the mean $M1$ strength. The over-all probability of detection of $M1$ transitions must therefore be of the order of 6%. It is thus possible that transition No. 13 is of $M1$ character. The next weakest transition, No. 23, occurs in appreciable strength from two capturing states, so that it is very unlikely to be $M1$. We therefore assign 1^+ or 1^- character to the level at 2555 keV only. All assignments are listed in column 4 of Table I.

c. Missing and Overlap of Levels

As mentioned above, the threshold of detection is about 0.36 times the mean $E1$ strength for the thermal spectrum and closer to one mean $E1$ strength for the resonance spectra. If we again assume a Porter-Thomas distribution[16] for the strengths, then the over-all probability of missing an $E1$ transition to a 1^+ state, which may occur from any of the 4 capturing states, is $\sim$13%. For transitions to 0^+ or 2^+ states, where these are allowed only from the 1^- capturing states, the probability of failing to detect a transition is correspondingly higher, being estimated at 42%. These figures are used later in the paper in analyzing the distribution of $E1$ strengths.

Another possible distortion of the spectrum is the overlap of levels within the resolution function of the spectrometer. This probability is negligibly small for

[12] L. V. Groshev, A. M. Demidov, V. N. Lutsenko, and V. I. Pelekhov, *Atlas of γ-Ray Spectra from Radiative Capture of Thermal Neutrons*, translated by J. B. Sykes (Pergamon Press, Ltd., London, 1959).

[13] R. E. Segel, R. K. Smither, and R. T. Carpenter, Phys. Rev. **133**, B583 (1964).

[14] B. P. Maier, U. Gruber, H. R. Koch, and O. W. B. Schultz, Z. Physik **185**, 478 (1965).

[15] C. E. Porter and R. G. Thomas, Phys. Rev. **104**, 483 (1956).

[16] See Sec. 4 A d.

levels of the same spin and parity, but the possibility of the overlap of 2^+ or 0^+ levels with those of 1^+ character must be considered. The spacing of observable 0^+ or 2^+ levels is $\sim$300 keV. If the two sets of levels are uncorrelated, then the probability of a 1^+ level lying within $\pm$15 keV of an observable 0^+ or 2^+ level is $\sim$10%. One such case of overlap is known at 1573 keV and this computation suggests that there may well be another undetectable case of overlap within our sample of 17 or 18 1^+ states.

These calculations of losses and overlap suggest that in the first 3.3 MeV of excitation of ^{200}Hg there are some 19 or 20 levels of 1^+ character and about the same number of 0^+ or 2^+ levels, although the latter number is subject to a much larger uncertainty, say $_{-5}^{+10}$.

d. Distribution of Strengths

In analyzing the distribution of $E1$ strengths, we assume that over the restricted energy range studied, 4.67–8.02 MeV, the $E1$ matrix elements are approximately energy-independent and fluctuate in some random manner determined by the overlap integrals of the nuclear wave functions involved. The object of the analysis is to find the distribution law for the squares of the nuclear matrix elements which nuclear theory suggests should belong to the χ^2 family of functions. We therefore remove the classical E^3 energy dependence of the observed transition strengths in order to obtain a set of "reduced strengths" which are proportional to the squares of the nuclear matrix elements.

In order to plot the distribution of these reduced strengths and to compare this with theory, it is necessary to divide each reduced strength by the mean of the population to which it belongs. In this experiment we have two different populations corresponding to the 0^- and 1^- capturing states which show different mean reduced strengths ($\langle S_0\rangle$ and $\langle S_1\rangle$). The observed ratio $\langle S_0\rangle/\langle S_1\rangle$, after correcting for missed and overlapping levels, is 2.02$\pm$0.56. The two populations were divided by their appropriate means, and the histogram obtained, corrected for missing and overlapping levels, is shown in Fig. 3. The intervals in the histogram were taken to be $\langle S\rangle/2$ since this was in all cases larger than the uncertainty on the experimental values. The distribution should therefore not be appreciably affected by the statistical accuracy of the individual experimental measurements.

We wish to compare the experimental histogram with the χ^2 family of curves. These curves are described by the formula

$$\rho_\nu(x)dx=((\nu/2)^{\nu/2}/\Gamma(\nu/2))x^{(\nu-2)/2}\exp(-\nu x/2)dx,$$

where $x=S/\langle S\rangle$ and ν is a quantity called the number of degrees of freedom. The Porter-Thomas distribution,[15] which corresponds to real matrix elements, normally distributed about a mean of zero, is represented by $\rho_1(x)$. The exponential distribution (which would correspond to complex matrix elements with real and imaginary parts each separately normally distributed with equal variances about a mean value of zero) is represented by $\rho_2(x)$.

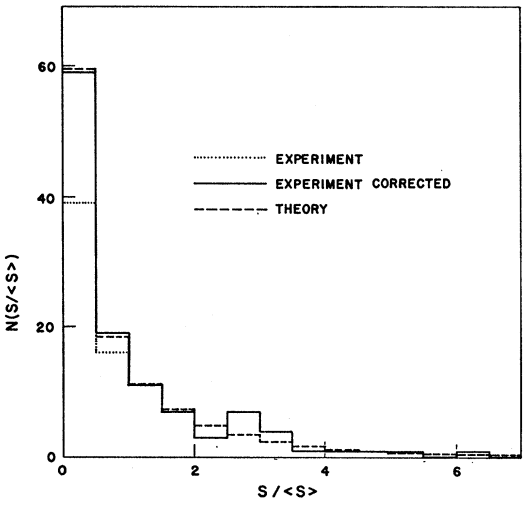

FIG. 3. Corrected experimental histogram showing distribution of reduced strengths for 88 $E1$ transitions in ^{200}Hg. The Porter-Thomas distribution is shown for comparison.

The comparison between the theoretical and experimental distributions was accomplished by computing the theoretical histograms for $\nu=0.5, 0.6, 0.7, \cdots, 1.9, 2.0$ and normalizing them to the total area under the experimental curve. A least-squares procedure was then followed to determine the best fit to the experimental curve, and Fig. 4 shows the values of χ^2 obtained plotted as a function of ν. In the fitting, the first six intervals of $S/\langle S\rangle$ were fitted separately, and the remainder of the tail was treated as a single interval because of the small number of counts involved. The number of degrees of freedom in the least-squares fitting is thus 6, so that the best fit obtained, for $\nu=0.96$, is excellent. A computation of the error on the best fit value yields

$$\nu=0.96_{-0.17}^{+0.24}.$$

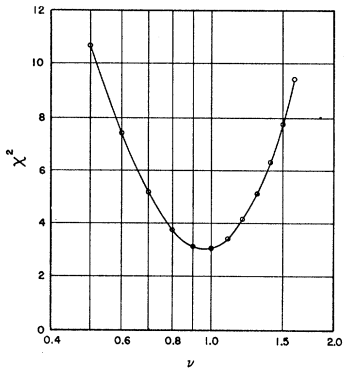

FIG. 4. Least-squares fit to experimental distribution of $E1$ strengths.

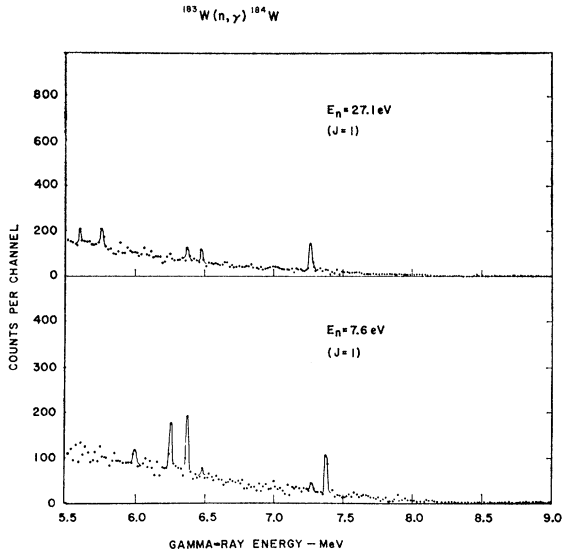

FIG. 5. Gamma-ray spectra for reaction $^{183}W(n,\gamma)^{184}W$.

The theoretical histogram shown in Fig. 3 is the Porter-Thomas distribution, $\nu=1$, and the closeness of the fit is obvious. An exponential distribution of the reduced strengths ($\nu=2$) is not compatible with our results.

B. $^{183}W(n,\gamma)^{184}W$

^{183}W, like ^{199}Hg, has spin and parity $\frac{1}{2}^-$, giving compound states 0^- and 1^- for capture of s-wave neutrons. The two resonances studied, at 7.6 and 27 eV, both have 1^- character. The data obtained on these resonances are shown in Fig. 5 and the results of an analysis of the areas under the principal peaks are listed in Table II. The agreement between the measured strengths and those quoted by Bollinger and collaborators (normalized to 4.9% for the 7413-keV ground-state transition) is fairly good. The sample of transition strengths obtained was not large enough to permit an analysis of the distribution, but large fluctuations occur in the strengths of transitions which is qualitatively in agreement with a small value of ν.

C. $^{198}Hg(n,\gamma)^{199}Hg$ and $^{182}W(n,\gamma)^{183}W$

These two target nuclei are even-even and have 0^+ spin and parity assignments. They thus form compound states of $\frac{1}{2}^+$ character when an s-wave neutron is captured so no ambiguity exists concerning the spin of the capturing state.

Several qualitative features stand out in these results which are shown in Figs. 6 and 7. There is a strong group of lines in the 23-eV resonance in mercury with energies below 5296 keV. These are not seen in the 90-eV resonance and may be due to capture in a different isotope. ^{204}Hg has a binding energy of 5480 keV for an additional neutron and we have analyzed the data on ^{198}Hg on the assumption that the lower group of lines is due to capture in ^{204}Hg. The result of the analysis is shown in Table III. If all the lines are really due to capture in ^{198}Hg, then the strengths of transitions in the 23-eV resonance should be reduced by about a factor of 2.

Interesting features seen in Fig. 7 are the presence of a very strong line (19% of captures) in the 4-eV resonance at a gamma-ray energy of 5167 keV which is very much weaker in the other two resonances, and the absence of any observable transitions of 5893 keV to the state at 207 keV in the 4-eV spectrum. This state is, however, strongly populated from the 114-eV

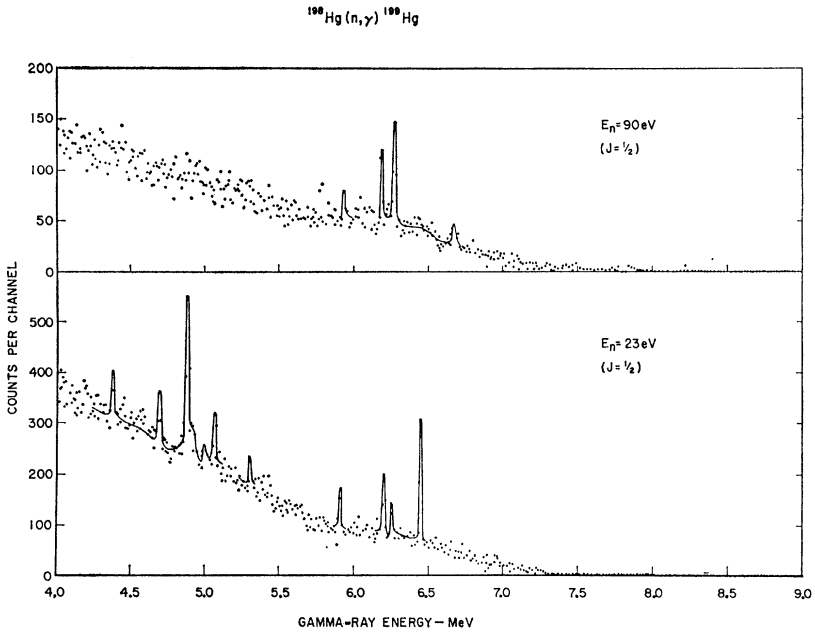

FIG. 6. Gamma-ray spectra for reaction $^{198}Hg(n,\gamma)^{199}Hg$.

TABLE II. Strengths of transitions in reaction $^{183}W(n,\gamma)^{184}W$ expressed as number of transitions per hundred captures.

No.	E_γ (keV)	Energy of final state (keV)	J^π	Transitions per hundred captures: 7.6 eV ($J=1$) This work I_γ (%)	This work ΔI_γ	Ref. 1 I_γ (%)	Ref. 1 ΔI_γ	27 eV ($J=1$) This work I_γ	This work ΔI_γ	Ref. 1 I_γ	Ref. 1 ΔI_γ
1	5631	1782	$0^+, 1^+, 2^+$	0	0.6			1.4	0.5		
2	5791	1622	$0^+, 1^+, 2^+$	0.4	0.6			3.2	0.5		
3	6022	1391	$0^+, 1^+, 2^+$	2.2	0.6			−0.1	0.4		
4	6288	1125	2^+	5.1	0.6	2.66	0.14	0.9	0.4	0.60	0.06
5	6408	1005	$1^+, 2^+$	5.4	0.6	3.57	0.21	2.0	0.3	0.57	0.10
6	6511	902	2^+	0.5	0.4	0.23	0.15	1.5	0.3	1.22	0.08
7	6723	690	0^+	0	0.3	0.21	0.08	0	0.3	−0.10	0.05
8	7302	111	2^+	0.7	0.3	0.15	0.23	2.9	0.3	2.79	0.17
9	7413	0	0^+	4.9	0.4	4.90[a]	0.23	0.2	0.2	0.11	0.17

[a] Reference 1 data normalized here.

resonance. These violent fluctuations show the danger of making deductions about nuclear structure from a spectrum due to capture in one state only, such as a thermal spectrum. The analysis of the $^{182}W(n,\gamma)^{183}W$ data is given in Table IV.

5. DISCUSSION

Previous work on the spectra of gamma rays following neutron capture was discussed by Bollinger and collaborators[1] in 1963. These measurements were made with sodium iodide crystals, so that only transitions to the first few excited states were observed. The best determination of ν for a single nuclide was obtained by Bollinger for capture in ^{195}Pt where 3 transitions were observed in 8 resonances, a total of 24 transitions for which a value[17] of $\nu=1.56\pm0.51\pm0.14$ was reported. By combining data on transitions in ^{78}Se, ^{184}W, and ^{200}Hg with those in ^{196}Pt, Bollinger was able to show that $\nu=1.34\pm0.33\pm0.21$, a result which favored the Porter-Thomas distribution with $\nu=1$.

More recently, Julien[2] described an analysis of sodium-iodide measurements at Saclay and also a reanalysis of the Argonne data, both of which, he said, gave results consistent with $\nu=2$. A study of 127 transitions following thermal capture in many different nuclei was made by Bartholomew[18] which also favored the exponential distribution ($\nu=2$). The fit, however, was poor, and Bartholomew pointed out that many of the thermal spectra corresponded to capture into more than one resonant state, which might be expected to yield $\nu>1$. On eliminating all such data, his sample was reduced to only 16 cases where a single resonance predominated. In this case, however, the most probable value of ν was unity, and the fit to the χ^2 function was good.

The present experiment, although containing assumptions about mean values of populations, and cor-

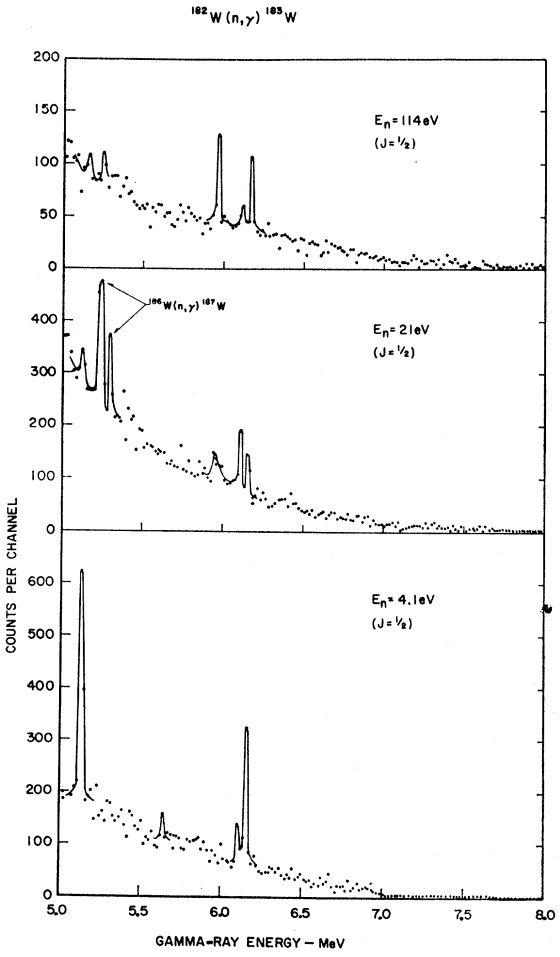

FIG. 7. Gamma-ray spectra for reaction $^{182}W(n,\gamma)^{183}W$.

[17] The first and second uncertainties quoted by Bollinger and collaborators represent, respectively, a statistical error depending upon the size of the sample, and a systematic error determined by the quality of the data.

[18] G. A. Bartholomew, in *Proceedings of the Conference on Electromagnetic Lifetimes and Properties of Nuclear States, Gatlinburg, Tennessee, 1961*, Nuclear Science Series Report No. 37 (National Academy of Science–National Research Council Publication 974, Washington 25, D. C., 1962), p. 209.

TABLE III. Strengths of transitions in reactions $^{198}Hg(n,\gamma)^{199}Hg$ and $^{204}Hg(n,\gamma)^{205}Hg$, expressed as numbers of transitions per hundred captures.

No.	E_γ (keV)	Energy of final state (keV)	J^π	Transitions per hundred captures 23 eV (204) I_γ (%)	ΔI_γ	23 eV (198) I_γ (%)	ΔI_γ	90 eV (198) I_γ (%)	ΔI_γ
1	4368	1112	$\frac{1}{2}^-, \frac{3}{2}^-$	12.2	2.6				
2	4682	798	$\frac{1}{2}^-, \frac{3}{2}^-$	12.8	2.5				
3	4875	605	$\frac{1}{2}^-, \frac{3}{2}^-$	35.3	2.5				
4	4905	575	$\frac{1}{2}^-, \frac{3}{2}^-$	7.6	2.4				
5	5060	420	$\frac{1}{2}^-, \frac{3}{2}^-$	9.5	2.1				
6	5296	184	$\frac{1}{2}^-, \frac{3}{2}^-$	3.9	2.0				
	(5480)	0	$\frac{1}{2}^-$						
7	5902	749	$\frac{1}{2}^-, \frac{3}{2}^-$			7.4	1.0	6.9	1.8
8	6159	492	$\frac{3}{2}^-$			1.3	1.0	15.5	2.3
9	6197	454	$(\frac{1}{2}^-)$			10.4	1.0	4.2	1.3
10	6249	402	$(\frac{1}{2}^-)$			5.1	1.0	20.0	2.2
11	6445	206	$\frac{3}{2}^-$			19.2	1.2	0.7	1.3
12	6651	0	$\frac{1}{2}^-$			0.4	0.6	5.4	1.2

TABLE IV. Strengths of transitions in reaction $^{182}W(n,\gamma)^{183}W$ expressed as numbers of transitions per hundred captures.

No.	E_γ (keV)	Energy of final state (keV)	J^π	Transitions per hyndred captures 4 eV I_γ (%)	ΔI_γ	21 eV I_γ (%)	ΔI_γ	114 eV I_γ (%)	ΔI_γ
1	5167	1023	$\frac{1}{2}^-, \frac{3}{2}^-$	19.4	1.1	3.1	1.2	1.4	1.2
2	5983	207	$\frac{3}{2}^-$	−0.1	0.4	2.4	0.5	7.1	1.1
3	6143	47	$\frac{3}{2}^-$	2.8	0.6	3.3	0.5	1.9	0.8
4	6190	0	$\frac{1}{2}^-$	9.0	0.7	2.6	0.3	5.3	1.0

responding corrections for missed levels, would seem to provide by far the largest sample of reduced $E1$ strengths (88) studied in a single nucleus, so that the value found[19] for ν of $0.96_{-0.19}^{+0.24}$ would seem to be conclusive evidence that the distribution of the reduced strengths is of Porter-Thomas and not exponential form, and that the matrix elements for high-energy transitions following resonance neutron capture are essentially real.

Another interesting feature of these results is the contrast in reduced strength between the transitions from the 1^- capturing states to the low-lying collective levels and those to the levels above 1255 keV, many of which are presumably mainly of a particle-excitation nature. If we quote these transition strengths as mean partial radiation widths reduced to a photon energy of 1 MeV, then the mean width for the collective levels is 7.1 ± 3.6 μeV and for the higher excited states is 43.9 ± 8.8 μeV, showing a significant difference in the matrix elements. This comparison can be extended to other target nuclei, and measurements on ^{183}W as target (Fig. 7) show no such increase in transition strength to states above 1 MeV in the highly distorted compound nucleus ^{184}W. The mean reduced partial radiation width to the well-resolved states below 1800 keV is 4.7 ± 1.6 μeV, comparable with the value for the low-lying states in ^{200}Hg. This effect is also seen in the odd compound nuclei ^{199}Hg and ^{183}W, where no pairing energy gap exists (Figs. 5 and 6). For these nuclei, our results give mean reduced partial radiation widths for the transitions listed in Tables III and IV of 50 ± 20 μeV and 13.6 ± 4.3 μeV, respectively. The possibility of obtaining mean reduced widths for particular transitions or groups of transitions averaged over several resonances is perhaps the most important feature of the application of germanium spectrometers to the study of resonance neutron capture. One may hope that many systematic effects will be observed in future work which will prove to be of value in the understanding of nuclear structure.

[19] The errors quoted for the present work are obtained from the least-squares fitting and therefore include both uncertainties quoted by Bollinger. The error due to the finite sample size is, however, predominant.

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