Thermal-Neutron-Capture Gamma Rays in Yb^{170}, Yb^{172}, and Yb^{174}

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A Ge(Li) detector was used to investigate the γ spectra following thermal neutron capture in enriched isotope targets of Yb^{170}, Yb^{172}, and Yb^{174}. In addition to capture in these isotopes, γ lines were identified as resulting from thermal capture in Yb^{171} and Yb^{173}. The neutron separation energies of Yb^{171}, Yb^{172}, Yb^{173}, Yb^{174}, and Yb^{175} were found to be 6616, 8023, 6365, 7465, and 5819 keV, respectively. The experimental error is ±3 keV in all cases. For capture by the even-even isotopes, the energies and intensities of γ transitions originating from the capture state are presented together with the spins and Nilsson assignments of the low-lying rotational bands which they populate. Our measurements are compared with those in other experiments, and the results of our measurements are discussed. Regularities in the decay of the capture state to low-lying Nilsson levels have now been observed in comparing thermal neutron capture by different even-even nuclei in the region $A=176$. The regularities include relatively strong population of Nilsson bands with Λ equal to zero or 1 as compared to population of bands with Λ greater than 1. In addition, there seems to be a preference for the capture state decaying to particle rather than hole bands. A purely statistical version of thermal neutron capture would not seem to hold in this mass region.

I. INTRODUCTION

WITHIN the past two years, experiments on thermal capture by even-even nuclei in the mass region $A\approx176$ have shown several interesting regularities. For a set of six nuclei in this region, there are very strong $E1$ transitions to Nilsson states which have a third Nilsson number, Λ of zero or 1. $E1$ transitions to other states which are quite permissible from the point of view of over-all spin and parity (such as states with a spin of $\frac{3}{2}^-$ but with $\Lambda=2$) are either not populated or are populated with reduced intensity. For example, following thermal capture by Hf^{178}, Hf^{180}, W^{182}, and W^{186}, intense γ transitions proceed from the capture state to the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels in the $\frac{1}{2}^-$ [510] Nilsson band, while transitions to the $\frac{3}{2}^-$ [512] band head are much weaker.[1–6] A similar situation[7] exists for the reaction $Er^{166}(n,\gamma)Er^{167}$. In this reaction, the γ spectrum is dominated by two strong transitions to the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels in the $\frac{1}{2}^-$ [521] band while transitions to other $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels are of lower intensity.

To see if these regularities continue to hold in still more cases, we decided to study thermal capture by Yb^{170}, Yb^{172}, and Yb^{174}. These reactions involve neutron capture by even-even nuclei with masses between those of erbium and hafnium and should add an interesting set of cases to those already mentioned.

Our experimental arrangement and method are described in Sec. II. In Sec. III our data and results are presented and compared with other known data on these nuclei—in particular, the data on $Yb^{174}(n,\gamma)Yb^{175}$ by Bondarenko *et al.*[8] Finally, in Sec. IV, we discuss the results on the three Yb nuclei presented here together with those on $Yb^{168}(n,\gamma)Yb^{169}$ of E. B. Shera *et al.*[9] This discussion points out regularities which may exist among the Yb nuclei and includes pertinent results for (d,p) and (d,t) reactions on the even-even Yb nuclei.[10]

II. EXPERIMENTAL ARRANGEMENT AND METHODS

Figure 1 shows our experimental arrangement. The samples were placed in an external neutron beam from the tangential hole of the Naval Research Laboratory Reactor. The γ rays resulting from neutron capture were detected by a 30-cm^3 cylindrically drifted Ge(Li) detector. The combined resolution of the detector and electronics was typically 9 keV at 6 MeV. Data from the detector were collected in a 4096 channel analyzer which was stabilized by means of a spectrum stabilizer. The stabilizer held a voltage pulse from a precision pulser at a fixed channel near the end of the spectrum.

The detector was shielded from reactor background by a 30-cm cube of lead having a 10-cm-diam hole through its center to allow room for the detector. The lead in turn was shielded from neutron background by sheets of cadmium about 0.8-mm thick. Paraffin moderator was placed around the cadmium.

To shield the detector and the front of the lead house from neutrons, two sheets of Li^6 foil, about 350 mg/cm^2 each, and a block of $LiCO_3$ powder about 2.5-cm thick were placed between the detector and the sample. The background was quite low with this arrangement. Between the energies of 8.0 and 2.5 MeV our back-

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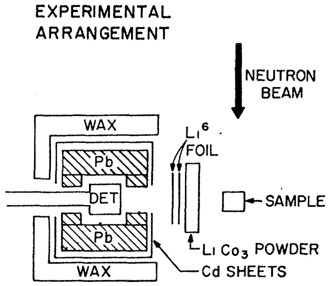

FIG. 1. Experimental arrangement.

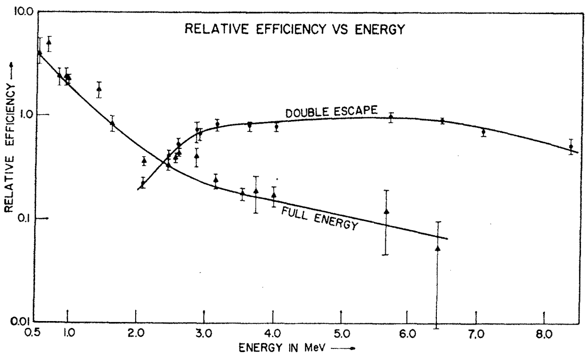

FIG. 2. Calibration curve. Relative efficiencies for both double escape and full energy are shown.

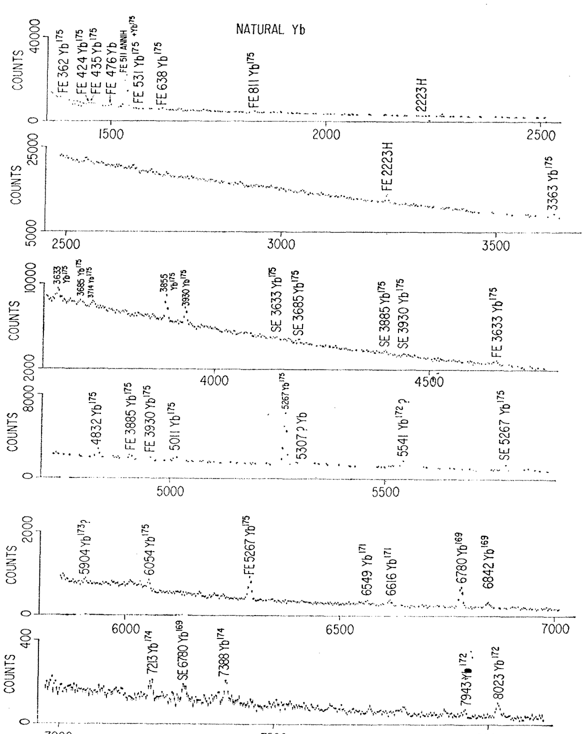

FIG. 3. Spectrum of natural Yb. Only lines in Yb and the most conspicuous background lines are labeled. SE denotes known single-escape peaks and F or FE full-energy peaks. Isotopic identities refer to the daughter nucleus resulting from neutron capture. The energy scale correctly gives the energies of double-escape peaks.

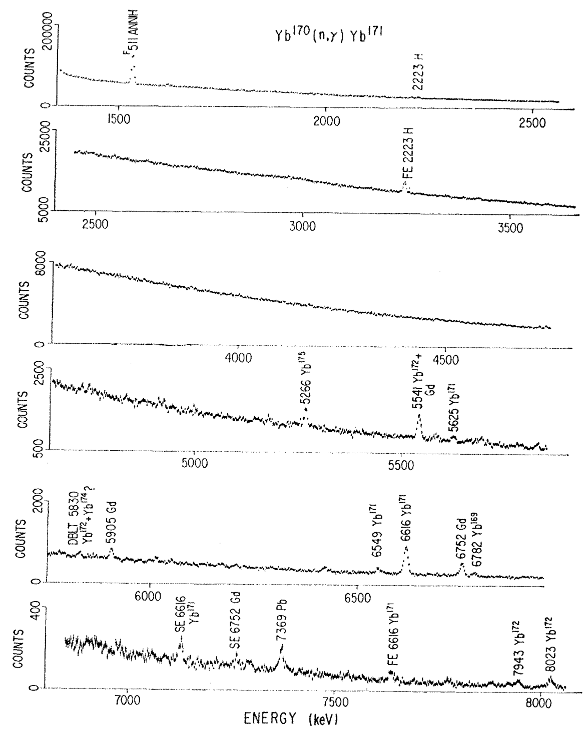

FIG. 4. Spectrum of $Yb^{170}(n,\gamma)Yb^{171}$. Only lines in $Yb^{170}(n,\gamma)$-Yb^{171} and the most conspicuous of other lines are labeled. The labeling and the energy scale follow the same conventions as in Fig. 3.

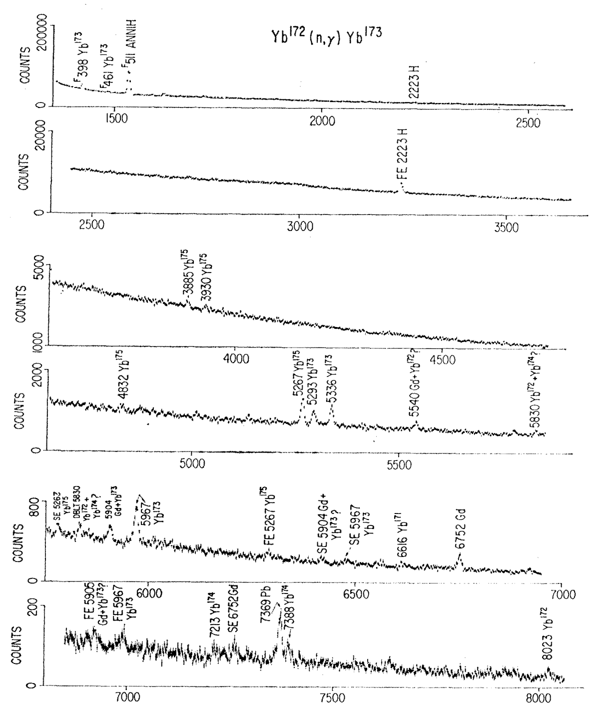

FIG. 5. $Yb^{172}(n,\gamma)Yb^{173}$. Only lines in $Yb^{172}(n,\gamma)Yb^{173}$ and the most conspicuous of other lines are labeled. The labeling and the energy scale follow the same conventions as in Fig. 3.

ground was essentially just a small amount of the lead capture γ ray at 7369 keV.

The energy calibration and the variation of relative efficiency with energy were obtained using both a sodium azide target and a sodium hydroxide target. Information on both nitrogen[11] and sodium[12] capture spectra were used as reference energies and intensities. Figure 2 shows our curves of relative efficiency as a function of energy for both double-escape and full-energy peaks. These efficiency curves include the effects of the small amount of matter which we had between the target and the detector. Below an energy of 800 keV, the curves are somewhat uncertain.

To make isotopic identifications, five samples of Yb were used. These samples consisted of 100 g of natural Yb, 22.7 mg of enriched Yb^{174}, 114 g of enriched Yb^{172}, 17 g of enriched Yb^{170} and 5.7 g of enriched Yb^{176}. Both the Yb^{170} and Yb^{172} samples were found to have small amounts of gadolinium impurity, but it was easy to correct for this in analyzing our spectra. Table I shows the composition of our five samples.

TABLE I. Isotopic composition of targets.

	Abundance in target (%)				
Capturing isotope	Enriched Yb^{170}	Enriched Yb^{172}	Enriched Yb^{174}	Enriched Yb^{176}	Natural Yb
Yb^{168}	0.03	<0.02	<0.01	0.01	0.14
Yb^{170}	68.5	0.12	<0.02	0.02	3.03
Yb^{171}	15.90	1.93	0.08	0.11	14.31
Yb^{172}	7.75	92.76	0.20	0.26	21.82
Yb^{173}	2.86	2.88	0.52	0.30	16.13
Yb^{174}	3.90	2.00	98.97	1.81	31.84
Yb^{176}	1.05	0.27	0.22	97.50	12.73

Since all samples were packed in nalgene containers, our background was measured by substituting identical empty containers for each of the targets.

III. SPECTRA AND RESULTS

The γ spectra for thermal neutron capture by natural Yb, enriched Yb^{170}, enriched Yb^{172} and enriched Yb^{174} are shown in Figs. 3, 4, 5, and 6, respectively. Figure 7 is an example of a background spectrum. For all of these spectra, the energy scale correctly gives the energies of double-escape peaks. Single-escape and full-energy peaks are appropriately labeled.

Table II shows the γ ray-energy and relative intensities for the reaction $Yb^{170}(n,\gamma)Yb^{171}$. In addition, the relative reduced matrix elements are shown assuming an E^3 law for $E1$ transitions. The last two columns of

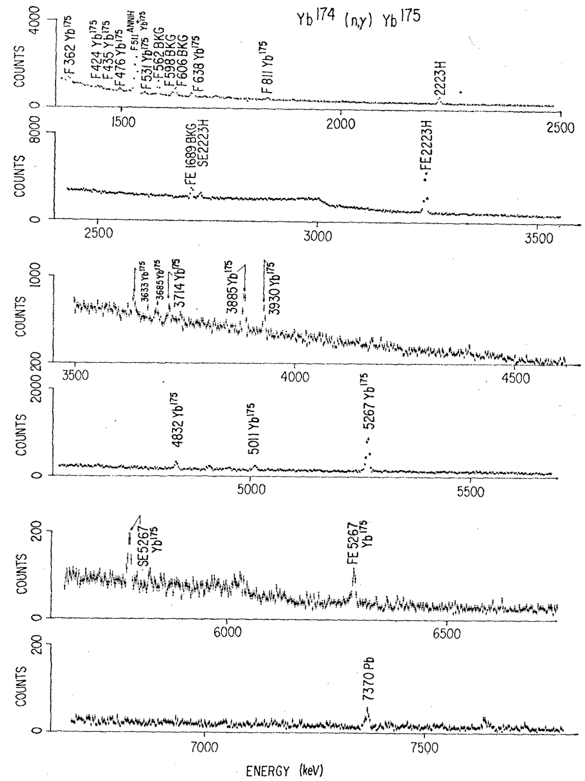

FIG. 6. Spectrum of $Yb^{174}(n,\gamma)Yb^{175}$. Only the lines in $Yb^{174}(n,\gamma)Yb^{175}$ and the most conspicuous of other lines are labeled. The labeling and the energy scale follow the same conventions as in Fig. 3.

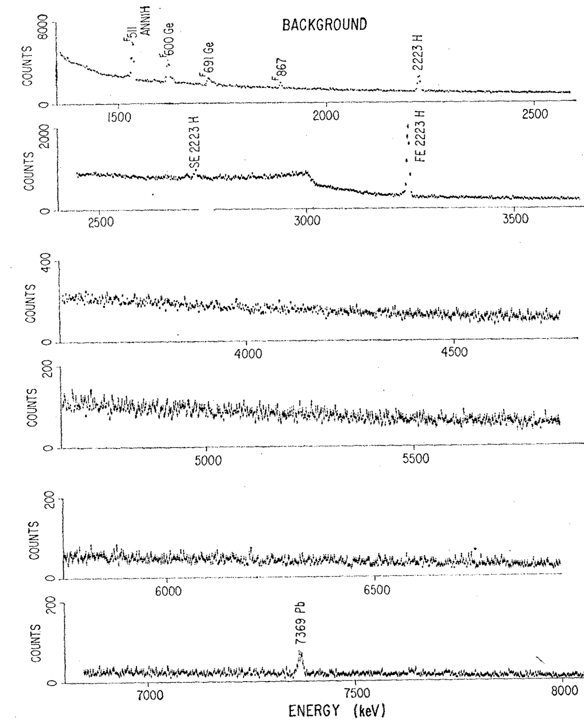

FIG. 7. Background spectrum. The labeling of lines and the energy scale follow the same conventions as in Fig. 3.

[11] G. E. Thomas, D. E. Blatchley, and L. M. Bollinger, Nucl. Instr. Methods **56**, 325 (1967).

[12] N. L. Rasmussen, V. J. Orphan, Y. Hukai, and T. Inouye, Nucl. Data **A3**, 405 (1967).

TABLE II. High-energy γ lines resulting from $Yb^{170}(n, \gamma)Yb^{171}$. All energies are in keV. Uncertainty is ± 3 keV. Neutron-separation energy is 6616 ± 3 keV.

Energy of line	Relative intensity	Relative reduced matrix element ($E1$ or $M1$ transitions)	Levels populated Energy	Spin	Nilsson Assignment
6616	1.00 ± 0.05	1.00 ± 0.05	0	$\frac{1}{2}$	$\frac{1}{2}^-$ [521]
6549	0.15 ± 0.05	0.15 ± 0.05	67	$\frac{3}{2}$	$\frac{1}{2}^-$ [521]
5625[a] (Doublet)	0.10 ± 0.05	0.16 ± 0.08	987? and 995	$\frac{3}{2}$	unknown $\frac{1}{2}^-$ [510]

[a] Doublet probably populates two close levels in Yb^{171}.

TABLE III. High-energy γ lines resulting from $Yb^{172}(n, \gamma)Yb^{173}$. All energies are in keV. Uncertainty is ± 3 keV. Neutron-separation energy is 6365 ± 3 keV.

Energy of line	Relative intensity	Relative reduced matrix element ($E1$ or $M1$ transitions)	Levels populated Energy	Spin	Nilsson assignment
5967	0.97 ± 0.09	0.69 ± 0.07	398	$\frac{1}{2}$	$\frac{1}{2}^-$ [521]
5904	0.21 ± 0.10	0.15 ± 0.08	463	$\frac{3}{2}$	$\frac{1}{2}^-$ [521]
5336	1.00 ± 0.09	1.00 ± 0.09	1031	$\frac{1}{2}$	$\frac{1}{2}^-$ [510]
5293	0.74 ± 0.15	0.76 ± 0.15	1073	$\frac{3}{2}$	$\frac{1}{2}^-$ [510]

TABLE IV. High-energy lines in $Yb^{174}(n, \gamma)Yb^{175}$. All energies are in keV. Uncertainty is ± 3 keV. Neutron-separation energy is 5819 ± 3 keV.

Present work Energy	Rel. int.	Previous work[a] Energy	Rel. int.	Relative reduced matrix elements ($E1$ or $M1$ transitions)	Level populated Energy	Spin	Nilsson assignment	Comments
5307	<3	5307	2.3	<3	511	$\frac{1}{2}$	$\frac{1}{2}^-$ [510]	
5267	100 ± 8	5267	100	100 ± 8	552	$\frac{3}{2}$	$\frac{1}{2}^-$ [510]	
5011	13 ± 3	5012	15	15 ± 3	808	$\frac{3}{2}$	$\frac{3}{2}^-$ [512]	
		4904	<0.3					b
4832	19 ± 4	4832	19	25 ± 5	987	$\frac{3}{2}$	$\frac{1}{2}^-$ [521]	
		4620?	3		1199			
4463	<6	4460	6	<10	1356			c
4407	<4	4407	7	<7	1412			d
4200	6 ± 3	4200	9	12 ± 6	1619	$\frac{3}{2}$	$\frac{3}{2}^-$ [521]	
4175	7 ± 3	4170?	8	14 ± 6				
3930	25 ± 4	3930	46	60 ± 10				
3885	40 ± 4	3885	80	100 ± 10				
3714	10 ± 3	3715	30	29 ± 9				
3685	11 ± 4	3685	15	32 ± 12				
3633	33 ± 7	3635	41	100 ± 21				

[a] Reference 8.
[b] In the present work the full-energy peak of the 3885-keV γ ray accounts for all of the intensity observed at 4907 keV. This full-energy peak would certainly hide a very small peak at 4904 keV.
[c] Compton edge of 3685 peak?
[d] Compton edge of 3633 peak?

TABLE V. Low-energy lines in $Yb^{174}(n,\gamma)Yb^{175}$. All energies are in keV. Uncertainty is ±3 keV. Neutron-separation energy is 5819±3 keV. Relative intensities in the present work differ from those in the previous work because different lines were chosen as intensity standards. However, the ratio of the intensity of a line in our work to the intensity of the same line in the previous work should be constant except for experimental error.

Present work Energy	Present work Rel. Int.	Previous work[a] Energy	Previous work[a] Rel. Int.	Ratio of intensities: previous work to present work	Comments
811	20±4	811	510	25	
638	24±4	639.4	615	24	
531	7±3	534.1	180	26	
511		514.4	3550		b
476	15±4	476.2	305	20	
435	11±4	434.8	215	20	
424	11±4	428	245	22	
362	17±4	353.1	360	21	

[a] Reference 8.
[b] The intensity of this line is difficult to estimate because of the presence of annihilation radiation at nearly the same energy. This line appears in our spectrum as a slight broadening of the annihilation line at 511 keV.

Table II show the energies, spins, and Nilsson assignments of the levels populated (with the usual assumption that high-energy γ lines which are well above half the neutron-separation energy of the nucleus originate from the capture state). Table III is a similar table for the reaction $Yb^{172}(n,\gamma)Yb^{173}$. The energies and spins of levels observed in the experiment are in good agreement with those observed in (d,p) and (d,t) work as reported by Burke *et al.*[10] The neutron-separation energies of Yb^{171} and Yb^{173} were found to be 6616±3 and 6365±3 keV, respectively, which is also in good agreement with the neutron-separation energies of (d,p) and (d,t) work.[10]

The results for the reaction $Yb^{174}(n,\gamma)Yb^{175}$ are presented in Tables IV and V together with those of Bondarenko *et al.*[8] The energy measurements of the present work and that of Bondarenko *et al.* are in excellent agreement and are well within the quoted errors. Relative intensity measurements are also in good agreement for all lines except those at 3930, 3885, and 3714 keV. Even accounting for the experimental error in our data and an upper limit of 20% in the experimental error of Ref. 8, it is difficult to reconcile the two sets of data. In our data, the measured intensities of the 3885-, 3930-, and 5267- keV (the reference line for intensities) lines have essentially the same ratios in the spectra from the three targets in which they were clearly seen—natural Yb, Yb^{174}, and Yb^{172}. It would seem unlikely, therefore, that the presence of interfering impurities or the isotopic misidentification of any of the lines could explain the discrepancy. Another possible source of error would be an error in the relative-efficiency curve used to correct the data. Our relative-efficiency curve in this region has been checked several times. In addition, since we had little mass between the target and detector, we would expect our curve of relative efficiency versus energy to be essentially that of the Ge(Li) detector itself for this region of energy. Our detector in fact, does, compare well with other detectors of similar size and shape for the energy range in question.[13]

Lines reported in Ref. 8 at 5307, 4904, 4463, and 4407 keV were not observed by us. The line at 5307 keV is not excluded by our data and a line at 4904 keV would be hidden by the full-energy peak of the 3885-keV γ ray. At 4463 and 4407 keV, we observe barely perceptible Compton edges which we attribute to the 3685- and 3633-keV peaks. Our upper limit for these lines is somewhat less than the intensity of Ref. 8.

Tables VI and VII show lines identified as resulting from $Yb^{171}(n,\gamma)Yb^{172}$ and $Yb^{173}(n,\gamma)^{174}$, respectively. The neutron-separation energies of Yb^{172} and Yb^{174} are measured to be 8023±3 and 7465±3 keV, respectively.

TABLE VI. High-energy γ lines resulting from $Yb^{171}(n,\gamma)Yb^{172}$. All energies are in keV. Their error is ±3 keV. Neutron-separation energy is 8023±3 keV. Spin of capture state is 0^-, 1^-.

Energy of line	Relative intensity	Levels populated Energy (present value)	Levels populated Energy (previous value)[a]	Spin
8023	1.00±0.05	0	0	0^+
7943	0.43±0.12	80	79	2^+
5830[b] (Doublet)	0.03±0.02	2193		
5541[c]	6.4±2.2	2482		

[a] Reference 14.
[b] Doublet seems to consist of two lines: one in $Yb^{171}(n,\gamma)Yb^{172}$ and one in $Yb^{173}(n,\gamma)Yb^{174}$, which are close in energy. Because of the large uncertainty of this line, its existence is questionable. In Ref. 14 a level at 2193 keV has been identified; however, its spin is 4^+, which makes it unlikely that the 5830-keV line populates this level.
[c] Line from Gd impurity near this line makes its intensity difficult to measure.

[13] J. E. Cline, I.E.E.E. Trans. Nucl. Sci. **NS-15**, 198 (1968).

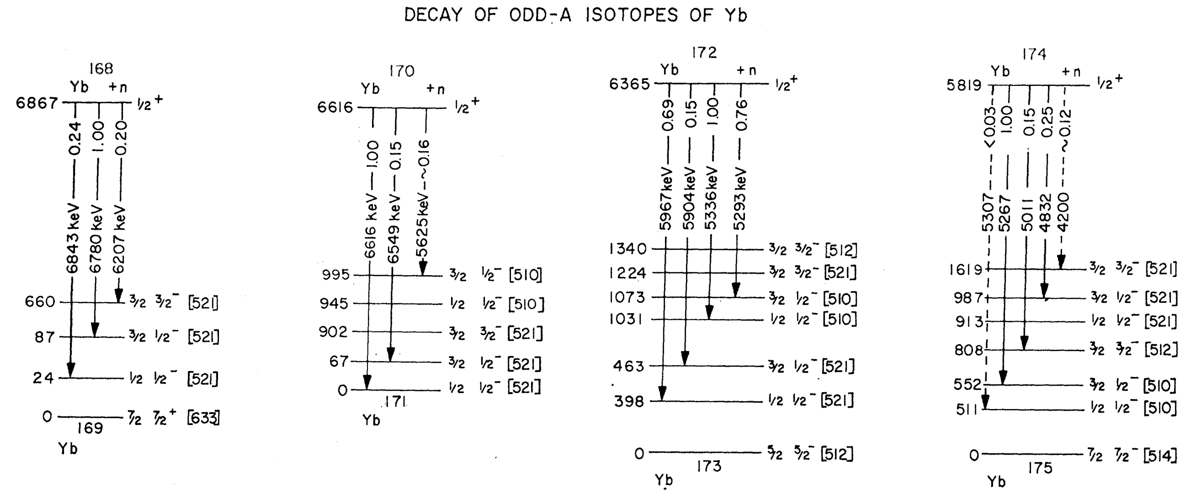

FIG. 8. Decay of the capture states for odd isotopes of Yb. Each γ line is labeled with its energy and its relative reduced-transition probability. Levels are labeled on the left with their energy in keV and on the right with their spins and Nilsson assignments. Except for the ground states, only levels which could be populated by $E1$ and $M1$ transitions from the capture state (that is, only excited levels with spins of $\frac{3}{2}$ or $\frac{1}{2}$) are shown. Questionable transitions are shown in dashed lines.

Our neutron-separation energies and measured levels are in good agreement with the (d,p) and (d,t) work of Burke *et al.*[10] and of Burke and Elbek.[14]

We also searched for γ lines resulting from neutron capture in Yb^{176} by placing an enriched Yb^{176} target in our thermal beam. The few weak lines observed in the Yb^{176} target did not occur in any of the other targets and the possibility that they were impurities could not be completely eliminated.

IV. DISCUSSION

Figure 8 shows the direct transitions from the capture state for the reactions $Yb^{170}(n,\gamma)Yb^{171}$, $Yb^{172}(n,\gamma)Yb^{173}$, and $Yb^{174}(n,\gamma)Yb^{175}$ as well as for $Yb^{168}(n,\gamma)Yb^{169}$.[9] The intensities shown on the lines are relative reduced matrix elements assuming an E^3 law for $E1$ transitions.

Comparing the spectra from capture by the even-even Yb isotopes reveals several interesting features. For example, in the cases of $Yb^{172}(n,\gamma)Yb^{173}$ and $Yb^{174}(n,\gamma)Yb^{175}$, where the $\frac{1}{2}^-[510]$ and $\frac{3}{2}^-[512]$ bands in the daughter nuclei are both identified, the $\frac{3}{2}^-[512]$ band is less strongly populated by transitions originating from the capture state for both reactions. This is very similar to the situation observed for neutron capture by the even-even hafnium and tungsten nuclei. Another interesting feature is the fact that the $\frac{3}{2}^-[521]$ band head—which is identified as a hole state in Yb^{173} and Yb^{175} according to (d,p) and (d,t) reactions[10]—is not very strongly populated by direct transitions from the capture state.

Still another interesting feature to note is the behavior of transitions to the $\frac{1}{2}^-[521]$ and $\frac{1}{2}^-[510]$ bands as one starts with neutron capture by Yb^{168} and progressively adds two neutrons to the capturing nucleus until one arrives at capture by Yb^{174}. In the two daughter nuclei Yb^{169} and Yb^{171}, the decay spectra are dominated by transitions from the capture state to the $\frac{1}{2}^-[521]$ band. In Yb^{171} only a weak transition goes to the $\frac{1}{2}^-$ level in the $\frac{1}{2}^-[510]$ band. Upon adding two neutrons to Yb^{171}, this ground-state band becomes filled and the $\frac{1}{2}^-[521]$ levels should take on a hole nature. (d,p) and (d,t) data[10] show that, in fact, this band is more strongly populated in (d,t) than in (d,p) for Yb^{173}. When we turn to the (n,γ) reaction producing Yb^{173}, we see that here the $\frac{1}{2}^-[521]$ band is still significantly populated, but not so strongly populated with respect to the other bands as it was in Yb^{169} and Yb^{171}. In Yb^{173} the $\frac{1}{2}^-[510]$-particle band is populated by somewhat larger reduced matrix elements than the $\frac{1}{2}^-[521]$ band. In the reaction $Yb^{174}(n,\gamma)Yb^{175}$, where in Yb^{175} the $\frac{1}{2}^-[521]$ band takes on a more definite hole nature, this band is still more weakly populated.

These regularities in the Yb nuclei, when combined with similar results on other nuclei in this region,

TABLE VII. High-energy γ lines resulting from $Yb^{173}(n,\gamma)Yb^{174}$. A'l energies are in keV. Their error is ±3 keV. Neutron-separation energy is 7465 ± 3 keV. Spin of capture state is 3^-, 2^-.

Energy of line	Relative intensity	Levels populated: Energy (present value)	Energy (previous value)[a]	Spin
7388	1.00 ± 0.20	77	77	2^+
7213	1.50 ± 0.70	252	252	4^+
5830[b] (Doublet)	1.9 ± 8.0	1635	1630	2^+

[a] Reference 14.
[b] Doublet seems to consist of two lines: one in $Yb^{171}(n,\gamma)Yb^{172}$ and one in $Yb^{172}(n,\gamma)^{174}$, which are close in energy.

[14] D. G. Burke and B. Elbek, Kgl. Danske, Videnskab. Selskab, Mat.-Fys. Medd. **36**, No. 6 (1967).

TABLE VIII Relative intensities for transitions from the capture state to low-lying Nilsson bands, namely, the $\frac{1}{2}^-$ [510] and $\frac{3}{2}^-$ [512] bands.

Product nucleus	Relative reduced-matrix elements $\frac{1}{2}^-$ [510] band $\frac{1}{2}^-$ level	$\frac{3}{2}^-$ level	Sum	$\frac{3}{2}^-$ [512] band $\frac{3}{2}^-$ level	Ratio (total to $\frac{3}{2}^-$ [512] band to total to $\frac{1}{2}^-$ [510])
Yb^{173}	1.00	0.76	1.76	~0	~0.00
Yb^{175}	<0.03	1.00	1.00	0.15	0.15
Hf^{179} [a]	8.8	1.1	9.9	~0	~0.00
Hf^{181} [a]	14.4	4.2	18.6	0.76	0.04
W^{183} [b]	100	36	136	~1	~0.01
W^{187} [b]	100	63	163	~2	~0.01

[a] Reference 1.
[b] References 2–6.

indicate that the state formed in the capture of thermal neutrons does show a decided preference for populating levels with Λ equal to zero or 1. In addition, the capture state decays preferentially to particle states rather than to hole states, and there is a rough correlation between the strength with which states are populated by (d, p) reactions and by (n, γ) reactions. Moreover, there is an anticorrelation between the strength with which states are populated in (d, t) reactions and in (n, γ) reactions.

It is interesting to note that when one averages over the resonances of nuclei in this mass region, the dominance of certain transitions seen in thermal capture does not occur. Bollinger and Thomas[15,16] have shown this by averaging over many resonances for capture by Er^{167}, Er^{164}, W^{182}, W^{184}, and W^{186}. An investigation by Garber *et al.*[17] has shown no significant difference in relative transition rates to the $\frac{1}{2}^-$ [510] and $\frac{3}{2}^-$ [512] bands for resonance capture by Hf^{178} and Hf^{180}. The resonant capture, therefore, does not disagree with a statistical theory such as that proposed by Porter and Thomas.[18]

It should also be pointed out that some irregularities exist in thermal capture. For both the $\frac{1}{2}^-$ [521] and $\frac{1}{2}^-$ [510] bands, the relative intensities of γ transitions to the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels in the same band vary widely from nucleus to nucleus. It is also possible that in the thermal capture by W^{184}, the transitions to the $\frac{1}{2}^-$ [510] band may be weaker than the one to the $\frac{3}{2}^-$ [512] band,[19] but the analysis of these data is not yet complete.

Nevertheless, a purely statistical theory for thermal capture would seem to lead to some difficulties. In the case of $Er^{166}(n, \gamma)Er^{167}$ alone, the work of Prestwich and Coté[7] has indicated that the transitions from the thermal-capture state to the $\frac{1}{2}^-$ [521] band are far too intense to agree with a Porter-Thomas distribution. In particular, they calculate that the probability of the 6228-keV transition to the $\frac{1}{2}^-$ [521] band head having the large intensity quoted in their paper is only $\sim 10^{-7}$. There are some ten cases of thermal neutron capture by even-even nuclei in the mass region $A \approx 174$ for which quantitative information is available. One would expect from a statistical model, in comparing transitions to the $\frac{1}{2}^-$ [510], $\frac{1}{2}^-$ [521], $\frac{3}{2}^-$ [512], $\frac{3}{2}^-$ [521] bands, that in one or more cases, the most intense transition would go to a band with $\Lambda > 1$ or to a well-defined hole band. Yet in no case where definite data are available does this occur.

In order to get a quantitative feel for how probable these enhanced transitions would be on the basis of a statistical model, let us calculate the probability distribution for the ratio of one reduced γ-matrix element to the sum of two others—for example, the single transition to the $\frac{3}{2}^-$ [512] band as compared with the sum of the two transitions to the $\frac{1}{2}^-$ [510] band. Suppose we assume that the matrix elements follow a χ^2 distribution with one degree of freedom.[20,21] Let r be the ratio of the intensity of a line to the sum of two others. The probability that this ratio will be between r and $r+dr$ is

$$P(r)\,dr = \tfrac{1}{2}r^{-1/2}(1+r)^{-3/2}. \qquad (1)$$

The probability that this ratio will be smaller than some maximum value R is

$$P_{r\leq R} = [R/(1+R)]^{1/2}. \qquad (2)$$

Table VIII shows the relative transitions to the $\frac{1}{2}^-$ [510] and $\frac{3}{2}^-$ [512] bands for Yb^{173}, Yb^{175}, Hf^{179}, Hf^{181}, W^{183}, and W^{187}. These nuclei were chosen since

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[17] D. I. Garber, D. Parks, O. A. Wasson, M. R. Bhat, and R. E. Chrien, Bull. Am. Phys. Soc., Ser. II, **13**, 64 (1968).

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

[19] M. J. Martin, J. A. Harvey, and G. G. Slaughter (private communication).

[20] Since thermal capture often involves more than one resonance and may include interference between resonances, this assumption is not always correct. Bartholomew (Ref. 21) has indicated that $\nu=2$ is usually a better value. However, it can be shown that a value of ν greater than 1 would only strengthen the following arguments.

[21] G. A. Bartholomew, *Proceedings of the Conference on Electromagnetic Lifetimes and Properties of Nuclear States, Gatlinburg, Tennessee, 1961* (Nuclear Science Series Report No. 37, National Academy of Sciences—National Research Council, Publication 974, Washington, D.C. 20025, 1962).

TABLE IX. Relative intensities for transitions from the capture state to low-lying Nilsson bands. The $\frac{1}{2}^-$ [510], $\frac{1}{2}^-$ [521], and $\frac{3}{2}^-$ [521] bands.

Product nucleus	$\frac{1}{2}^-$ [510] band $\frac{1}{2}^-$ level	$\frac{3}{2}^-$ level	Sum	Relative intensities $\frac{1}{2}^-$ [521] band $\frac{1}{2}^-$ level	$\frac{3}{2}^-$ level	Sum	$\frac{3}{2}^-$ [521] band $\frac{3}{2}^-$ level	Ratio ($\frac{1}{2}^-$ [510] sum to $\frac{1}{2}^-$ [521] sum)	Ratio ($\frac{3}{2}^-$ [521] to sum of both sums)
Dy[165] [a]				1.00	0.80	1.80	0.10		0.056
Er[167] [b]	0.0058	0.0082	0.0140	1.00	0.23	1.23	0.017	0.011	0.014
Yb[169]				0.24	1.00	1.24	0.20		0.17
Yb[171]	~0.0	~0.10	~0.10	1.00	0.15	1.15	~0	0.089	~0
Yb[173]	1.00	0.76	1.76	0.69	0.15	0.84	~0	2.09	~0
Yb[175]	<0.03	1.00	1.00	~0	0.25	0.25	0.12	4.00	0.096
Hf[179] [c]	8.8	1.1	9.9	~0	0.78	0.78		12.7	

[a] G. Markus, W. Michaelis, H. Schmidt, and C. Weitkamp, Z. Physik **206**, 84 (1967); R. K. Sheline, W. N. Shelton, H. T. Motz, and R. N. Carter, Phys. Rev. **136**, 351 (1964).

[b] Reference 7.

[c] References 1 and 22.

both bands were well identified in all the cases. In addition, the analysis is simplified in these cases since the transitions to the $\frac{1}{2}^-$ [521] band do not predominate (perhaps because it s a hole band[10,22]), and we have only to compare the relative populations of two different particle bands. The last column of Table VIII shows the intensity of the transition to the $\frac{3}{2}^-$ [512] band head divided by the total intensity to the $\frac{1}{2}^-$ [510] band. We note that the largest value for this ratio is 0.15—the value for Yb[175].

If nothing but a Porter-Thomas probability law holds, this should be exactly the same as picking three lines at random, and dividing the intensity of one line by the sum of the intensities of the other two. The probability that this ratio would be 0.15 or less in all six cases is about 2×10^{-3}. Since all but one of the values in Table VIII are substantially less than 0.15, this is an upper limit on the probability of this being totally a chance phenomenon. The distribution of ratios shown in Table VIII clearly does not agree with the distribution of Eq. (1).

As a check on whether a set of resonance γ transitions which did obey the Porter-Thomas law would agree with Eq. (1), we applied a Monte Carlo procedure to the data of Samour *et al.*[23] for the 66 γ lines which they found in three resonances of Pt[195]. In a thousand trials, three of the 66 lines were selected randomly—each line having the same probability of being picked. The intensity of the last line picked was divided by the sum of the intensities of the first two. The distribution of Eq. (1) was found to hold.

Table IX shows the relative intensities of transitions to the $\frac{1}{2}^-$ [510], $\frac{1}{2}^-$ [521], and $\frac{3}{2}^-$ [521] bands for Dy[165], Er[167], Yb[169], Yb[171], Yb[173], Yb[175], and Hf[179]. The ratio of the total intensity of the transitions to the $\frac{1}{2}^-$ [510] band divided by those to the $\frac{1}{2}^-$ [521] band is shown in the next to last column of Table IX. There are only five cases where both the $\frac{1}{2}^-$[510] and $\frac{1}{2}^-$[521] bands were both well identified. These ratios seem to be related to whether or not the $\frac{1}{2}^-$ [521] band is a particle or hole band. Such a correlation would not be expected from a purely statistical law. (We have already noted that the $\frac{1}{2}^-$ [510] band is relatively weakly populated when the $\frac{1}{2}^-$ [521] band is a particle band, and that the situation changes upon filling the $\frac{1}{2}^-$ [521] band.)

As another estimate of how much significance we may attach to the seeming avoidance of hole states, the last column of Table IX shows the ratio of the intensity of the transition to the $\frac{3}{2}^-$ [521] band head to the sum of the intensities of the four transitions going to the $\frac{1}{2}^-$ [521] and $\frac{1}{2}^-$ [510] bands. In all six cases where the $\frac{3}{2}^-$ [521] band was well identified, this ratio was less than 0.17. The chance of this ratio being 0.17 or less in all six cases is about 2.5%.

A more rigorous calculation would not increase this probability. For example, it might be argued that if one wishes to examine whether hole bands are weakly populated by transitions from the thermal-capture state, it is incorrect to sum the transitions to the $\frac{1}{2}^-$ [521] band with those to the $\frac{1}{2}^-$ [510] band in those nuclei where the $\frac{1}{2}^-$ [521] band is a hole band. (We did this in order to treat all the cases in a uniform manner.) However, in such cases we should compare the transition to the $\frac{3}{2}^-$ [521] band with the sum of only two transitions; the small ratios observed would then be even more improbable. In addition, in Dy[165] and Yb[169], the $\frac{1}{2}^-$ [510] band is not clearly identified. Nevertheless, we still did the computation on the basis of comparing the ratio of a single transition to the sum of four others.

The rather small probabilities which we have esti-

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mated here do not completely eliminate the possibility of a rather unusual statistical fluctuation. However, they do raise the question that perhaps some direct-capture or channel-resonance phenomena of the kind proposed by Lane and Lynn[24] may be occurring.

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Transitions in ^{107}Pd Following 22-min ^{107}Rh Decay*

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We have studied the decay of ^{107}Rh by γ-ray spectroscopy using Ge(Li) detectors and Ge(Li)-NaI(Tl) $\gamma\gamma$ coincidence techniques. A decay scheme has been constructed incorporating all but six of the 39 transitions reported. This decay scheme involves excited states in ^{107}Pd at 115.6, 302.8, 312.2, 348.2, 381.8, 392.5, 471.2, 567.7, 670.0, 1102, and 1148 keV. A half-life of 850±100 nsec was found for the 115.6-keV level, and $\gamma\gamma$ delayed-coincidence spectroscopy was employed to determine the features of the decay scheme related to this level. β branching ratios and log*ft* values have been derived from the relative γ-ray intensities and the β/γ ratio. We find that the β decay of ^{107}Rh tends to avoid populating ^{107}Pd levels that have strong single-particle character [that is, levels populated strongly in (d, p) and (d, t) reactions].

I. INTRODUCTION

Several years ago the decay of 22-min ^{107}Rh was studied[1] by scintillation spectroscopy. A number of β and γ transitions were fitted into a decay scheme, but the poor resolution of the measurements precluded any formulation of a decay scheme that was more than tentative.

Strong impetus for exploiting the better resolution now obtainable with semiconductor detectors stems from recent studies of ^{107}Pd levels by (d, p) and (d, t) spectroscopy[2–4]—particularly the high-resolution (d, p) work[3]—which established a number of new levels and produced information concerning some probable spins. These results were interpreted in terms of the distributions of single-particle strengths for the neutrons in the N=51–82 shell.

An investigation of the decay of ^{107}Rh is of interest in terms of a comparison of the types of information which can be obtained by β, γ spectroscopy versus reaction spectroscopy. The earlier decay-scheme work[1] indicated that the spin of ^{107}Rh is high, though not as great as $\frac{9}{2}$ units. In the single-particle model[5] the only high-spin configuration for the 45th proton in the ground state is $1g_{9/2}$. In the region of 45 protons or neutrons, $\frac{7}{2}+$ and $\frac{5}{2}+$ ground states are encountered frequently. The reason for this is not clear, but in any event the structures of these ground states are probably not simple (see, for example, Ref. 6). Thus one might expect the decay of ^{107}Rh to select states in ^{107}Pd which contrast with those strongly populated in ^{106}Pd(d, p) and ^{108}Pd(d, t) reactions, since the latter states presumably are, respectively, single-particle and single-hole states.

II. EXPERIMENTAL PROCEDURES AND RESULTS

A. Source Preparation

The ^{107}Rh was produced by reactor-neutron fission of ^{235}U. Ruthenium (including 4.2-min ^{107}Ru, which decays to ^{107}Rh) was isolated chemically. After an appropriate waiting period, ^{107}Rh was separated from the ruthenium.

In greater detail, the procedure was as follows: Uranyl nitrate solution (containing about 1 mg of ^{235}U) was irradiated for 5 min at a flux of 2×10^{12} n cm^{-2} sec^{-1}. Ruthenium carrier was added to the irradiated solution, and the solution was boiled to drive off the gaseous fission products. The ruthenium was distilled (as RuO_4)

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