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PHYSICAL REVIEW C VOLUME 2, NUMBER 5 NOVEMBER 1970

Low-Energy Gamma Rays from Resonant Neutron Capture in Tm^{169}[†]

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(Received 29 June 1970)

Low-energy γ rays following slow-neutron capture in thulium have been used to check the angular-momentum assignments of the neutron resonances. A previous discrepancy in the spin of the 17.5-eV resonance has been resolved. The correlation between reaction widths noted in previous work has been recalculated and found to be substantially unchanged. An isomeric state at 183.2 keV has been investigated by measuring the delay in the low-energy transitions involving this state, and a half-life of 3.2 ± 0.3 μsec is obtained, in fair agreement with previous work.

1. INTRODUCTION

This brief note on some new experimental data on the Tm^{169}(n, γ)Tm^{170} reaction is to be considered as an addendum to a paper by Lone *et al.*[1] In this paper, the emphasis was on the prompt high-energy γ rays from the resonance- and thermal-neutron capture in Tm^{169}. Additional data on the partial widths of the 151-eV resonance were reported by Chrien[2] at the Dubna Nuclear Structure Conference. In the present work, we have studied low-energy ($\leq$511-keV) γ rays from individual resonances in this nucleus. From these data, we have found it possible to (a) determine the spins of the neutron resonances and (b) find the half-life of an isomeric state at an excitation energy of 183.2 keV in Tm^{170}.

2. EXPERIMENTAL RESULTS

The data were obtained at the high-flux beam reactor fast chopper with a 37-c.c. Ge(Li) detector, a chopper speed of 10 000 rpm, and a flight path of 48.8 m. The Ge(Li) detector had a resolution of 3.8 keV at 511 keV. The thulium target was 3.8 $\times$3.8 in. with 179.4 g of Tm$_2$O$_3$, and the total running time for the experiment was 31 h. The time-of-flight spectrum obtained is shown in Fig. 1, where the resonance energies are given in eV. We are able to resolve resonances up to an energy of 115.2 eV. Some recent work by de Barros *et al.*[3] has shown that the resonance at 94.0 eV is made up of two closely spaced resonances at 93.5 and 94.0 eV, and we are not able to resolve these. The straight lines under the resonances indicate the scan limits set on the time-of-flight to obtain the γ-ray spectra originating by neutron capture in these resonances. Such spectra obtained from the 14.4- and 34.8-eV resonances are shown in Fig. 2 and are typical of the γ-ray spectra obtained from these resonances. The analysis of these spectra to obtain the resonance spins is discussed in the next section.

3. DETERMINATION OF THE SPINS OF THE *s*-WAVE NEUTRON RESONANCES

These low-energy γ rays observed in resonance capture represent transitions between the different low-lying levels of the compound nucleus Tm^{170} and are the result of these states being populated by a large number of the high-energy primary transitions. Hence, these γ rays represent some sort of an average over contributions from many intermediate states and do not show the wide intensity fluctuations characteristic of primary transitions. In spite of such an averaging, one can expect the intensities of these low-energy γ rays to

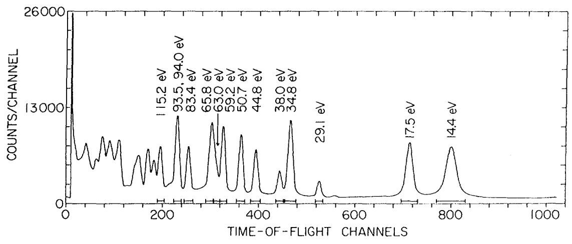

FIG. 1. Time-of-flight spectrum of thulium.

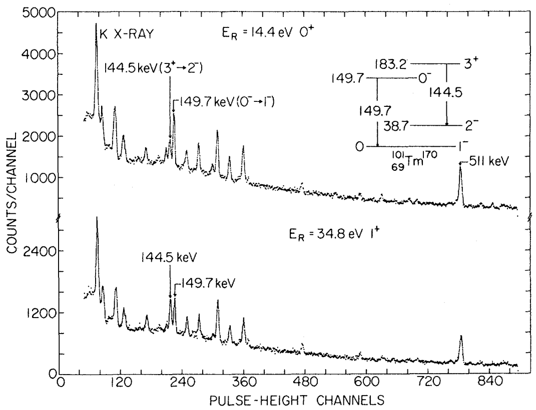

FIG. 2. Low-energy γ spectra from resonances in thulium.

TABLE I. Spin assignment of Tm resonances.

E_r (eV)	$\frac{I_\gamma\ (149.7\ \mathrm{keV})}{I_\gamma\ (144.5\ \mathrm{keV})}$	Present work	Asghar *et al.*	Singh
14.4	2.03 ± 0.12	0	0	0
17.5	2.24 ± 0.16	0	1	0
29.1	1.08 ± 0.09	1		
34.8	$.94 \pm 0.05$	1	1	1
38.0	1.28 ± 0.13	1		
44.8	1.12 ± 0.12	1	1	1
50.7	1.11 ± 0.08	1	1	1
59.2	1.06 ± 0.07	1	1	0
63.0	$.99 \pm 0.09$	1		
65.8	2.68 ± 0.22	0	0	0
83.4	1.13 ± 0.11	1	1	1
93.5				
94.0	1.19 ± 0.06	1	1	1
115.2	1.08 ± 0.08	1	1	1

depend on (i) the spins of the compound-nuclear state formed by neutron capture, (ii) the number of steps in the γ cascade, (iii) multipolarity of transition at each step, and (iv) spins of the different states involved in the cascade. These simple considerations arise solely from accounting for the population of final states which can connect with initial states by virtue of the selection rules governing electromagnetic radiation. The assumption is made that the decay proceeds by a purely statistical process, independent of the nuclear structure of the states involved, and in particular, independent of the final-state spin. Therefore, a systematic study of the intensity variation of these γ rays could enable us to determine the spins of the neutron resonances involved. Such differences were first observed by Draper *et al.*[4] in the spectra of the three lowest resonances in In^{115} with NaI(Tl) detectors. Similar measurements on the resonance neutron capture in Er^{167} and Hf^{177} were made by Fenstermacher *et al.*[5] These are even-odd nuclei and the low-energy transitions between the 6^+, 4^+, 2^+, and 0^+ levels of the even-even nuclei resulting from neutron capture were measured. These experimental ratios were interpreted in terms of the simple dipole γ-ray cascade model of Huizenga and Vandenbosch,[6] and resonance spins were assigned. Subsequently, the cascade model has been refined by Pönitz[7] and Sperber and Mandler[8] to include mixing of quadrupole transitions and energy-dependent factors in calculating the transition probabilities. Recently, similar measurements have been reported by Wetzel and Thomas[9] using Ge(Li) detectors and even-odd target nuclei such as Er^{167} and $\mathrm{Os}^{187,189}$. They have measured the transitions between the members of the rotational band of the even-even nuclei Er^{168} and $\mathrm{Os}^{188,190}$ and assigned some resonance spins.

The present experiment shows that the low-energy γ spectra from capture in the Tm resonances fall into two well-defined groups with respect to the intensities of the two prominent γ peaks at 144.5 and 149.7 keV. Typical members of these two groups are shown in Fig. 2. A cursory examination of these spectra shows that the intensity ratios of these two γ rays is about 1:2 in one group of resonances, typical of which is the spectrum from the 14.4-eV spin-0 resonance. In the other group, this intensity ratio is 1:1, and typical of these is the 34.8-eV spin-1 resonance. Part of the energy level diagram of Tm^{170} pertaining to these transitions is shown in Fig. 2 as obtained from the work of Sheline *et al.*[10] From this energy level diagram we notice that with a finite number of steps in the γ cascade, the 144.5-keV γ ray depopulating a 3^+ state could be expected to be less intense in the 0^+ spin resonances, as the 3^+ state is farther removed from the 0^+ than from the 1^+ spin state corresponding to the other group of resonances. This is indeed found to be true if we accept the resonance spins in Tm as measured by other techniques.[11,12] The measured ratios of the 149.7-keV

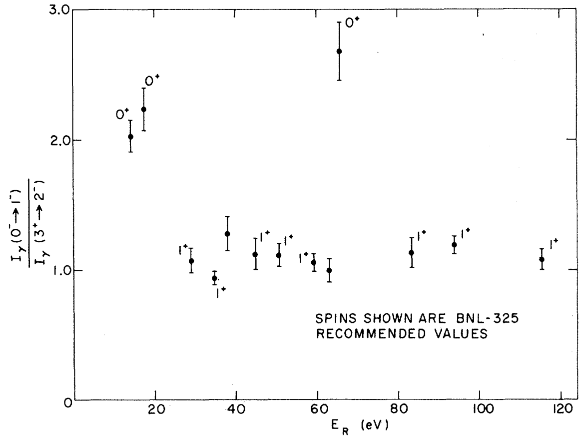

FIG. 3. Intensity ratio of the 149.7-keV γ ray to the 144.5-keV γ ray for the resonances of thulium.

γ ray to the 144.5-keV γ ray for the 13 resonances in Tm are given in column 2 of Table I and are also shown in Fig. 3. Clearly, these ratios fall into two well-defined groups. The resonance spins as measured by other techniques and as given by Goldberg *et al.*[13] are also shown in this figure. Using the refined analysis of Pönitz,[7] one could reproduce these ratios by assuming appropriate values for the γ-ray multiplicity, the level-spacing parameters, the multipole mixing ratios, and by including the specific nuclear-structure effects in Tm^{170}. Since these parameters are largely unknown, such detailed agreement with theory would be largely an exercise in curve fitting, and the point of view of the present work is to simply accept the experimental fact of the division of the spectra into two groups which can be associated with the capturing-state spin. From the data we can assign a spin of 1 to the 29.1-, 38.0-, and 63.0-eV resonances which are weak and where spins could not be determined by the usual methods.[11, 12] This, incidentally, points out one of the advantages of the present method over the scattering measurements which determine the resonance spins by measuring the statistical-weight factor g. The scattering measurements are difficult to carry out with weak resonances and are not very reliable with high-spin nuclei where the two values of g are close together. Such limitations do not apply to the present method. As a result of an interference analysis carried out in the previous paper,[1] a spin of 1 was assigned to the 17.5-eV resonance, whereas the present work indicates that its spin is 0. This agrees with the measurement of Singh,[11] and with earlier assignments[13] based on the absence of high-energy γ rays to final states of spins 0 and 2^-. The ambiguities inherent in the interference analysis coupled with the clear indications of the present experiment indicate that the correct assignment is zero. In Table I we summarize the spin assignments for the resonances in Tm from the present work and the measurements of Asghar *et al.*[12] and Singh.[11]

Considerable interest has been drawn to thulium because of the observed correlation of neutron reduced width and radiative widths.[14] Lone[1] and Chrien[2] analyzed these correlations, assuming that the 17.5-eV resonance has spin 1. The present experiment shows decisively that this spin assignment is in error. The deletion of the 17.5-eV resonance, however, causes very little change in the correlation coefficient. The average for the correlation coefficients over 15 final states is +0.33, omitting the 17.5-eV resonance, as contrasted with a previously reported value of +0.274. Furthermore, if we now include three spin-1 resonances previously omitted from consideration – those at 59.2, 115, and 153 eV – the average correlation coefficient becomes $R \equiv \langle \mathrm{corr}(\Gamma_n^0, \Gamma_{\gamma\lambda i}) \rangle_i = 0.304$. The quantity R is a sample estimate of the infinite-population and zero-error correlation coefficient ρ_M^2. The 10 and 90% confidence limits on ρ_M^2 as estimated from Monte Carlo calculations are 0.7 and 0.2, respectively. The change in spin assignment and the inclusion of additional resonances have made no significant change in the observed correlation.

4. DETERMINATION OF THE HALF-LIFE OF THE 183.2-keV ISOMERIC STATE IN Tm^{170}

The low-energy γ rays observed in resonance capture could be used to determine the half-lives of the isomeric states from which they originate, provided such half-lives are in the range of a few microseconds. This technique will be described elsewhere[15] and we will not go into the details here.

From the low-energy data, time-of-flight spectra corresponding to the 149.7-, 204.4-, and 511-keV γ rays were obtained, and the neutron resonances in these spectra do not show any displacement towards lower neutron energies as compared with the time-of-flight spectra of prompt high-energy γ rays.

However, the time-of-flight spectrum corresponding to the 144.5-keV γ ray depopulating the 183.2-keV state of Tm^{170} does show a displacement toward lower neutron energies in the time-of-flight spectrum. These two time-of-flight spectra are

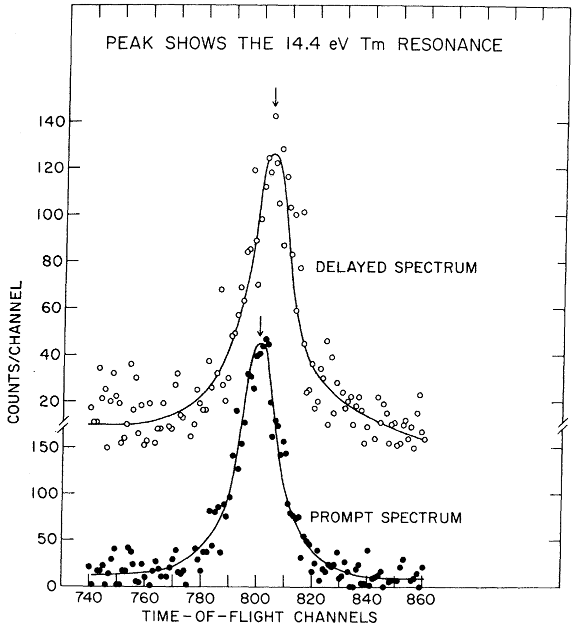

FIG. 4. Time-of-flight corresponding to the 149.7-keV γ ray ("prompt" spectrum) and the 144.5-keV γ ray ("delayed" spectrum).

shown in Fig. 4 and it is clear that the 14.4-eV resonance peak is displaced toward higher time-of-flight channels when scanned on the 144.5-keV γ ray, as compared with the corresponding scan on the 149.7-γ peak. It is possible, by a least-squares program,[15] to deconvolute the "delayed shape" using the "prompt shape" (149.7 keV) and obtained the half-life of the 183.2-keV isomeric state. The value obtained is 3.2 ± 0.3 μsec. This is to be compared with 4.25 ± 0.5 μsec by Andreev, Kästner, and Manfross[16] and 4.2 μsec by Berestovoi.[17]

ACKNOWLEDGMENT

The authors thank Dr. Mendel Beer for enlightening discussions on the statistical aspects of the correlation analysis.

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†Work supported by the U. S. Atomic Energy Commission.

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