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Properties of the excited states in ^{171}Tm

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Angular correlations of the 277.4-210.5 keV and the 371.9-277.4 keV γ-γ cascades in ^{171}Tm populated in the decay of the 7.5 h ^{171}Er have been measured to be $W(\theta)_{277.4-210.5} = 1 + (0.124 \pm 0.005)\, P_2(\cos\theta)$ and $W(\theta)_{371.9-277.4} = 1 + (0.018 \pm 0.012)\, P_2(\cos\theta)$. The result for the first cascade, combined with the existing data on high resolution internal conversion measurements, establishes the spin of the 635.4 keV level to be $\frac{7}{2}$, corresponding to the $\frac{7}{2}^+[404]$ Nilsson state. The spins of the 912.8 keV ($\frac{5}{2}$) and the 1284.7 keV ($\frac{5}{2}$) levels are in agreement with the angular correlation measurements. The multipole mixing ratios of the transitions are deduced to be: 210.5 keV—$E1 + (\lesssim 0.06)\%\, M2$; 277.4 keV—$M1 + (10 \pm 1)\%\, E2$; and 371.9 keV—$M1 + (9 \pm 3)\% E2$. The half-life of the 635.4 keV level has been measured by the γ-γ delayed coincidence method to be $T_{1/2} = 1.26 \pm 0.06$ nsec. The identity of the delayed level has been confirmed by the delayed gating technique. The transition probability of the 210.5 keV $E1$ transition has been evaluated and compared with the theoretical estimate and that of similar transitions in other nuclei in the region.

[RADIOACTIVITY ^{171}Er from ^{170}Er (n,γ), measured $\gamma\gamma(\theta)$, $\gamma\gamma$delay, $\gamma\gamma$delayed gating. ^{171}Tm levels, deduced I^π, $T_{1/2}$, δ, $T(E1)$, G_{E1}. Enriched target.]

I. INTRODUCTION

The decay of ^{171}Er to levels in ^{171}Tm has been studied earlier in detail.[1-10] High resolution internal conversion and γ ray measurements[10] established the level scheme of ^{171}Tm. A partial level scheme[10, 11] is shown in Fig. 1. The ground state of ^{171}Tm has been characterized as the $\frac{1}{2}^+[411]$ Nilsson state.[12] This has been confirmed by the direct measurement of the spin by the atomic beam magnetic resonance method.[13] The electromagnetic properties of the members of the ground state rotational band have been studied in detail.[14-19] The 424.8 keV level has been identified[10, 11] as the $\frac{7}{2}^-[523]$ intrinsic state. The suggested assignment[10, 11] of the 635.4 keV level is $\frac{7}{2}^+$, but the high resolution measurements do not exclude the possibility of spin and parity $\frac{5}{2}^+$ for this level. An objective of the present work was to assign unambiguously the spin of the 635.4 keV level by γ-γ angular correlation measurement.

$E1$ transitions between the $\frac{7}{2}^+[404]$ and $\frac{7}{2}^-[523]$ Nilsson states have been observed[20, 21] in ^{165}Ho and ^{169}Tm. The $\frac{7}{2}^+[404]$ level is expected in ^{171}Er also. If the 635.4 keV level could be assigned to be the $\frac{7}{2}^+[404]$ Nilsson state, the 210.5 keV transition from this state to the 424.8 keV level would be a similar $E1$ transition. It would be of interest to measure this transition probability and compare it with the Nilsson estimate.

In the present work the 277.4-210.5 keV and the 371.9-277.4 keV γ-γ angular correlations were measured in order to confirm the spin of the 635.4 keV level and to determine the mixing ratios of the transitions in conjunction with high resolution internal conversion measurements[10] as a check on the values obtained from nuclear orientation.[22] The half-life of the 635.4 keV level was measured by the 277.4 keV γ-210.5 keV γ delayed coincidence method. Since the 635.4 keV level is only weakly fed it is essential to ensure that the delayed coincidence observed indeed shows the decay of this level. This has been done by establishing the sequence of the γ rays populating and depopulating this level by delayed gating technique.

II. EXPERIMENTAL METHODS

A. Source preparation

Sources of the 7.5 h ^{171}Er were made by irradiating 97% enriched ^{170}Er in the pneumatic irradiation facility of the CIRUS reactor at Trombay for 30 min. The irradiated sample was dissolved in HCl. For γ-γ angular correlation measurements the source was a dilute solution of $ErCl_3$ in dilute HCl. For γ-γ delayed coincidence measurements the samples were made by evaporating to dryness a drop of the solution on a Perspex strip. Since the source is short lived several irradiations had to be made, using a new sample of ^{170}Er for each irradiation.

B. Angular correlation measurements

The angular correlation measurements were made using a fast-slow coincidence system having

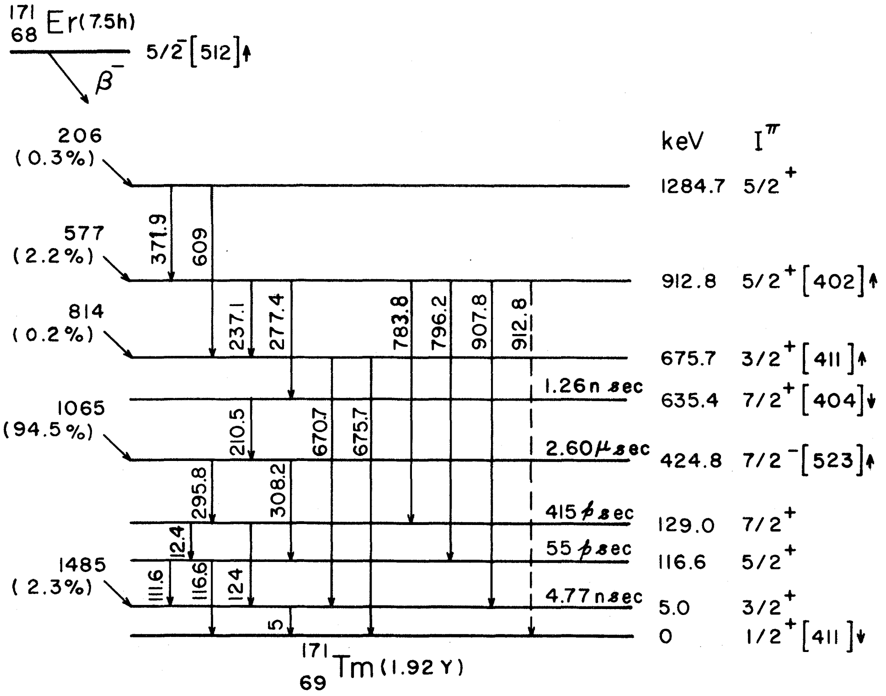

FIG. 1. Partial level scheme of ^{171}Tm.

a resolving time of $2\tau = 40$ nsec. Two scintillation detectors consisting of 3.8 cm diam × 2.5 cm thick NaI(Tl) crystals mounted on RCA 6810A photomultipliers were used. The detectors were placed at a distance of 7 cm from the source. Absorbers of 5 mm thick Perspex, 1 mm cadmium, and 0.1 mm copper were used to absorb β rays, x rays, and low energy γ rays. These minimized the effects of pile-up and coincidence summing in the spectrum. Lead cones lined inside with cadmium and copper were used to collimate the γ rays from the source and to minimize the effects of scattering. Sources of ^{171}Er of estimated strength 5–10 μCi at the start were used for the angular correlation measurements. After using each source for ~5 h it was replaced by a new one.

In the case of the 277.4-210.5 keV cascade, the photopeaks of the two γ rays were not clearly observable in the singles spectrum because of the intense 308.2 and 295.8 keV γ rays. The gates for the 277.4 and 210.5 keV γ rays were fixed by taking the coincidence spectrum with the other γ ray. The 308.2 and 295.8 keV γ rays contributed only to chance coincidences. Counts were observed with the movable counter at 90°, 120°, 135°, 150°, and 180°, counting for 10 min at each angle. The time of the start of the counting was noted for each angle. The coincidences and both the singles counts were recorded. In order to minimize systematic errors the angles between the counters were changed from 90° to 180° for one set of observations and from 180° to 90° for the next set, and so on. Chance coincidences were calculated from the observed singles counts at each angle, knowing the resolving time of the coincidence unit. The chance coincidences were also determined periodically by inserting a large delay in one of the channels and counting for a fixed time. The contribution of chance coincidences was on the average less than 10% of the observed coincidence counts.

The coincidence counts for each set of observations were corrected for chance coincidences and for decay of the source during the time between the start of counting at the first angle and the start at every other angle in a set. Since the singles counts had large contributions of the 308.2 and 295.8 keV γ rays the coincidence counts were not normalized with the singles counts. In order to ensure that there were no shifts or instabilities during measurements, only those sets of observations in which the singles count rates showed the exponential decay were accepted. A large number of such sets were collected totaling to more than 18 000 true coincidences at each angle. The corrected counts were finally fitted by the least-squares method to the correlation function $W(\theta) = 1 + A_2P_2(\cos\theta)$. As the 210.5 keV transition is known to be >99% $E1$ from internal conversion measurements,[10] the A_4 coefficient in the correlation function was assumed to be negligible. The

A_2 coefficient was corrected for attenuation due to the finite solid angle of the detectors. Corrections for the small contributions (≲3%) of interfering cascades, mainly the 371.9-277.4 keV cascade, were applied. These corrections were determined by analyzing the coincidence spectrum with the 277.4 keV γ ray in the same geometry and under the same conditions as used for the angular correlation measurements. The experimentally determined contributions were in agreement with those calculated from the known relative intensities[10] of the interfering cascades under the conditions of the experiment. The corrected correlation coefficient is $A_2(277.4\text{-}210.5) = 0.124 \pm 0.005$.

The 371.9-277.4 keV cascade being very weak, coincidence observations were made at angles 90°, 135°, and 180° only. Approximately 8000 true coincidences were observed at each angle. The corrected coincidences were analyzed as above. The A_4 term was assumed to be negligible. The A_2 coefficient was corrected for the estimated contributions (≲5%) of interfering cascades. The corrected value is: $A_2(371.9\text{-}277.4) = 0.018 \pm 0.012$.

C. Life-time measurements

In order to measure the life-time of the 635.4 keV level, the delay between the 277.4 keV and 210.5 keV γ rays was measured using a time-to-pulse-height converter (TAC) and two scintillation detectors consisting of 3.2 cm diam × 2.5 cm thick NaI(Tl) crystals mounted on RCA 8575 photomultipliers. Two constant-fraction discriminators were used to shape the anode pulses for the START and STOP inputs of the TAC. A weak ^{171}Er source of estimated strength ~5 μCi was used for the measurement. An anti-Compton shield with a 5 mm hole at the center, where the source was kept, minimized the effect of scattering from one detector to another. β rays and x rays were absorbed using suitable Perspex and cadmium absorbers. The source was at a distance of ~1 cm from either detector. The energy gates for the slow coincidence were chosen approximately between 260–285 keV for the 277.4 keV γ ray and 195–220 keV for the 210.4 keV γ ray. The TAC output gated by the slow coincidence output was recorded in a 512-channel analyzer. A typical TAC spectrum of the 277.4-210.5 keV cascade is shown in Fig. 2. The absence of a large prompt peak in the spectrum of ^{171}Er probably shows that spurious contributions due to scattering and any interfering cascades are negligible (see Sec. II D). The decay of the time spectrum was followed for several half-lives of ^{171}Er in order to ensure that the delayed events followed the 7.5 h half-life of ^{171}Er. No counts attributable to any long-lived impurities were observed after complete decay of ^{171}Er. Figure 2 also shows the prompt spectrum as obtained by using a ^{22}Na source of approximately the same strength as the ^{171}Er source and with the same energy gates as above. The prompt slope was 0.5 nsec. The calibration of the TAC was made by using standard 50Ω cables which were calibrated by measuring known half-lives.[23, 24] Several runs of ^{171}Er were made to improve the statistical accuracy of the data. The half-life of the 635.4 keV level was obtained by a least squares fit of the delayed part of the time spectrum to be $T_{1/2} = 1.26 \pm 0.06$ nsec.

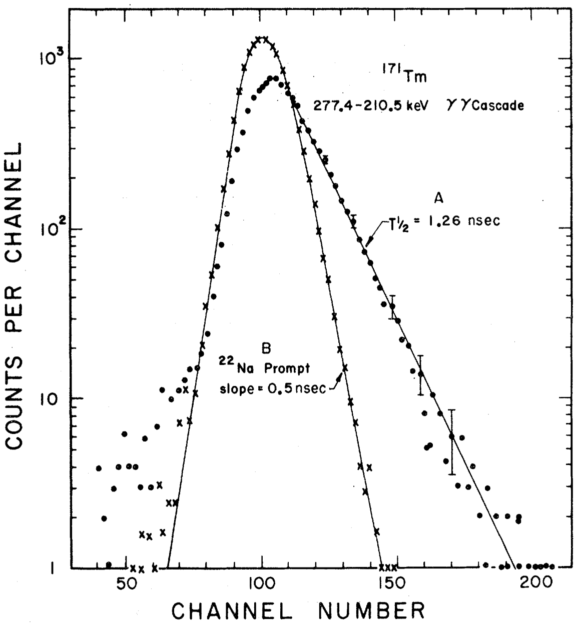

FIG. 2. Curve A, the delayed coincidence spectrum of the 277.4-210.5 keV γ-γ cascade in ^{171}Tm; curve B, the prompt spectrum using a ^{22}Na source under the same conditions as curve A.

D. Delayed gating measurements

The 277.4-210.5 keV cascade being very weak (only ~0.5% of the decays of ^{171}Er give rise to the 277.4-210.5 keV γ-γ cascade), it is necessary to ensure that the observed delayed spectrum is really due to this and not any other cascade. In order to do this the preceding and following γ ray sequences were established by delayed gating technique. The same set up as used for the life-time measurements was employed. The TAC output was gated using a single channel analyzer so that events corresponding to a delay of ~3 to 10 nsec were selected. The linear output of the STOP detector was gated at the photopeak region of the 210.5 keV γ ray. The slow coincidence output of these two was used to gate the γ spectrum in the START channel and the gated spectrum was stored in the multichannel analyzer. The coincidence spectrum so observed corresponds to γ rays preceding the 210.5 keV γ ray. This is shown in Fig. 3, curve A. A prompt coincidence spectrum ($2\tau \approx 40$ nsec) with the 210.5 keV γ ray is also shown in the figure (curve B) for comparison. This was taken by opening the window of the single channel analyzer so as to accept the full TAC spectrum and repeating the above run. The 277.4 keV peak and a weak 371.9 keV peak are observed in the spectrum preceding the 210.5 keV γ ray. This is in agreement with the 635.4 keV level being the delayed one (see Fig. 1).

The dynode output of the START channel detector was gated at the photopeak region of the 277.4 keV γ ray and the TAC output corresponding to a delay of ~3 to 10 nsec gated as before. The slow coincidence output of these two was used to gate the γ spectrum in the STOP channel. The gated spectrum was recorded using the multichannel analyzer. This gives the γ spectrum delayed with respect to the 277.4 keV γ ray (Fig. 4, curve A). The delayed spectrum showed the 210.5 keV peak and a composite peak of 295.8 + 308.2 keV γ rays (the latter mostly due to chance coincidences). Figure 4, curve B shows the spectrum in prompt coincidence ($2\tau \approx 40$ nsec) with the 277.4 keV γ ray. These observations confirm that the TAC spectrum of ^{171}Er in Fig. 2 shows the delay between the 277.4 and 210.5 keV γ rays.

III. RESULTS AND DISCUSSION

Analysis of the angular correlation coefficient A_2 for the 277.4-210.5 keV cascade was made assuming spin $\frac{7}{2}$ and $\frac{5}{2}$ for the 635.4 keV level. The internal conversion measurements of Graham, Geiger, and Johns[10] show that the 210.5 keV transition is $E1$ with $\lesssim 0.06\%$ $M2$ admixture and the 277.4 keV transition is $M1$ with possible $E2$ admixture. From the observed γ transitions from the 912.8 keV level[10] the spin of this level is $\frac{5}{2}$. The angular correlation coefficient for the 277.4-210.5 keV cascade when analyzed in conjunction

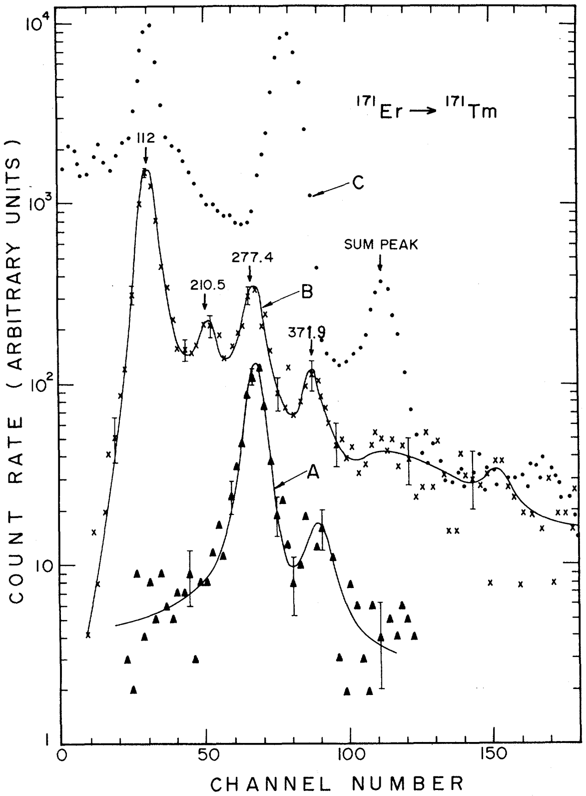

FIG. 3. Curve A, spectrum of γ rays preceding the 210.5 keV γ ray; curve B, the γ ray spectrum in prompt coincidence ($2\tau \approx 40$ nsec) with the 210.5 keV γ ray; curve C, singles spectrum.

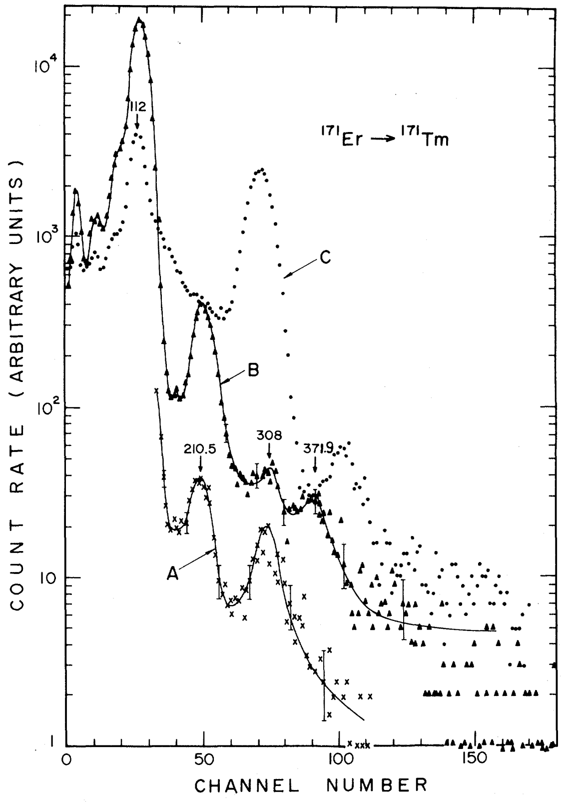

FIG. 4. Curve A, spectrum of γ rays delayed with respect to the 277.4 keV γ ray; curve B, the γ ray spectrum in prompt coincidence ($2\tau \approx 40$ nsec) with the 277.4 keV γ ray; curve C, the singles spectrum.

TABLE I. Results of γ-γ angular correlation measurements.

γ-γ cascade	A_2	Transition (keV)	δ	Multipolarity
277.4-210.5	0.124 ± 0.005	210.5	⋯	$E1 + (\lesssim 0.06)\%\ M2$ [a]
		277.4	-0.34 ± 0.02	$M1 + (10 \pm 1)\%\ E2$
371.9-277.4	0.018 ± 0.012	371.9	$+0.33 \pm 0.05$	$M1 + (9 \pm 3)\%\ E2$

[a] Calculated from internal conversion measurements of Ref. 10.

with the above results of internal conversion measurements gives no solution for spin $\frac{5}{2}$ for the 635.4 keV level, but gives agreement with spin $\frac{7}{2}$. This confirmed the identification of this level as the $\frac{7}{2}^+[404]$ Nilsson state. The mixing ratio of the 277.4 keV transition as obtained from the analysis of the angular correlation coefficient is $\delta = -0.34 \pm 0.02$, corresponding to a $(10 \pm 1)\%$ quadrupole admixture. The mixing ratios are defined in terms of the γ ray emission matrix elements.[25] The mixing ratio of the 277.4 keV transition obtained in the present work agrees with that obtained from the study[22] of oriented ^{171}Er. Any attenuation of the correlation due to possible extranuclear effects will not change the conclusions above except that the magnitude of the mixing ratio will be slightly different. From the analysis of the 371.9-277.4 keV correlation, the mixing ratio of the 371.9 keV transition has been obtained. The results of analysis of the present angular correlation measurements are shown in Table I. The sign of the mixing ratio of the 371.9 keV transition obtained in the present work is the opposite of that given in Ref. 22. This discrepancy in the sign has not been explained.

The transition probability for the 210.5 keV $E1$ transition has been calculated from the above results to be $T_\gamma(E1, \frac{7}{2}' \to \frac{7}{2}) = 5.2 \times 10^8\ \text{sec}^{-1}$. The $E1$ γ ray matrix element G_{E1} as defined by Nilsson[12] is deduced using the relation

$$T_\gamma(E1, I'K' \to IK) = 3.83 \times 10^{14} (Z/A)^2 A^{1/3} E_\gamma^{\,3} \times |\langle I1KK'-K | I1I'K' \rangle|^2 G_{E1}^{\,2},$$

where the symbols have their usual meanings. The experimental value of the matrix element is $|G_{E1}|_{\text{exp}} = (0.97 \pm 0.03) \times 10^{-3}$ which may be compared with the Nilsson estimate $G_{E1(\text{Nils})} = 1.00 \times 10^{-3}$. The present experimental value for ^{171}Tm is also in agreement with those of transitions between the same Nilsson states in other nuclei in the region.[20, 21]

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[1] E. N. Hatch and F. Boehm, Phys. Rev. 108, 113 (1957).

[2] S. A. E. Johansson, Phys. Rev. 105, 189 (1957).

[3] F. P. Cranston, Jr., M. E. Bunker, and J. W. Starner, Phys. Rev. 110, 1427 (1958).

[4] M. S. El-Nesr and M. R. El-Aassar, Z. Phys. 189, 138 (1966).

[5] D. E. Raeside, J. J. Reidy, and M. L. Wiedenbeck, Nucl. Phys. A114, 529 (1968); Bull. Am. Phys. Soc. 12, 36 (1966).

[6] A. Artna and M. W. Johns, Can. J. Phys. 39, 1817 (1961).

[7] D. G. Megli, G. P. Agin, V. R. Potnis, and C. E. Mandeville, Nucl. Phys. A107, 217 (1968).

[8] J. S. Geiger, R. L. Graham, and M. W. Johns, Bull. Am. Phys. Soc. 13, 672 (1968); R. L. Graham, G. T. Ewan, and J. S. Geiger, Nucl. Instrum. Methods 9, 245 (1960); R. L. Graham, J. S. Geiger, and M. W. Johns, in Contributions to the International Symposium on Nuclear Structure, Dubna, USSR, 1968 (unpublished), p. 44; in *Nuclear Structure: Dubna Symposium, 1968, Invited Papers* (IAEA, Vienna, 1968), p. 135.

[9] M. S. El-Nesr, Z. Naturforsch 25a, 1043 (1970).

[10] R. L. Graham, J. S. Geiger, and M. W. Johns, Can. J. Phys. 50, 513 (1972).

[11] D. J. Horen and B. Harmatz, Nucl. Data B11, 549 (1974).

[12] B. R. Mottelson and S. G. Nilsson, K. Dan. Vidensk.

Selsk. Mat. Fys.—Skr. 1, No. 8 (1959); S. G. Nilsson, K. Dan. Vidensk. Selsk. Mat. Fys.—Medd. 29, No. 16 (1955).

[13] A. Y. Cabezas, I. Lindgren, and R. Marrus, Phys. Rev. 122, 1796 (1961).

[14] J. P. Bocquet, J. Phys. (Paris) 26, 795 (1965).

[15] T. Sundstrom, J. O. Lindstrom, P. Sparrman, and J. Lindskog, Ark. Fys. 26, 397 (1964).

[16] R. B. Begzhanov and Kh. M. Sadykov, Zh. Eksp. Teor. Fiz. Pis'ma Red. 4, 436 (1966) [transl.: JETP Lett. 4, 294 (1966)].

[17] C. E. Turner, Jr., and E. N. Hatch, Bull. Am. Phys. Soc. 17, 559 (1972).

[18] Y. K. Agarwal, C. V. K. Baba, and S. K. Bhattacherjee, Phys. Lett. 14, 214 (1965).

[19] E. N. Kaufmann, J. D. Bowman, and S. K. Bhattacherjee, Nucl. Phys. A119, 417 (1968).

[20] K. P. Gopinathan and S. B. Patel, in *Proceedings of the International Conference on Nuclear Physics, Munich, 1973,* edited by J. de Boer and H. J. Mang (North-Holland, Amsterdam/American Elsevier, New York, 1973), Vol. 1, p. 300; S. B. Patel and K. P. Gopinathan, Nucl. Phys. and Solid State Phys. (India), 15B, 451 (1972); S. B. Patel, A. P. Agnihotry, and K. P. Gopinathan, *ibid.* 15B, 457 (1972) (The half-life of the 635.4 keV level reported in this reference is in error).

[21] K. P. Gopinathan and S. B. Patel, in Proceedings of the International Conference on Gamma-ray Transition Probabilities, Delhi, India, 1974 (to be published).

[22] K. S. Krane, C. E. Olsen, and W. A. Steyert, Nucl. Phys. A197, 352 (1972).

[23] K. P. Gopinathan, A. P. Agnihotry, S. B. Patel, and M. S. Bidarkundi, J. Phys. Soc. Jpn. Suppl. 34, 430 (1973).

[24] S. B. Patel, A. P. Agnihotry, P. N. Tandon, and K. P. Gopinathan, Phys. Rev. C 9, 1515 (1974).

[25] K. S. Krane and R. M. Steffen, Phys. Rev. C 2, 724 (1970).