Perturbed beta-gamma directional correlation in ^{170}Tm decay*

J. K. Tuli† and G. T. Emery
Physics Department, Indiana University, Bloomington, Indiana 47401
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Measurements of the perturbed directional correlation for the $1^- \rightarrow 2^+ \rightarrow 0^+$ β-γ cascade in ^{170}Tm ground state decay have been performed with a fast-slow coincidence system using a time-to-pulse-height converter and a double-focusing magnetic spectrometer. A liquid source in the form of a solution in dilute HCl was used. The unattenutated A_2 coefficient was found to be -0.179 ± 0.018 for electrons of energy $W = 1.5\ mc^2$; this value, when combined with the attenuation rates observed in our samples, is consistent with most previously reported values for the time-integrated coefficient.

[RADIOACTIVITY ^{170}Tm [from ^{169}Tm(n,γ)]; measured $\beta\gamma(\theta,t)$; deduced extranuclear attenuation, unattenuated $\beta\gamma(\theta)$. Liquid source, β spectrometer, plastic scintillators.]

I. INTRODUCTION

First-forbidden nonunique β transitions which deviate from the ξ approximation[1] can be very usefully employed in the study of nuclear structure. This is done through extraction of the nuclear matrix elements involved. The decay of ^{170}Tm provides an example of such a transition. This nucleus ($T_{1/2} \approx 127$ day) decays $\approx 23\%$ of the time to the 2^+ first excited state of ^{170}Yb, with an end-point energy of 883 keV. The decay scheme of ^{170}Tm is shown in Fig. 1.

Several measurements of the directional correlation between the inner (883 keV) β group of ^{170}Tm and the following 84.3-keV γ ray have been performed in the past.[2-12] The large value of logft for this transition (9.3) and its not-too-small β-γ directional correlation are perhaps consequences of its departure from the ξ approximation. This departure is further confirmed by the observation of a nonstatistical spectrum shape in several independent measurements.[13-16] In addition to this failure of the ξ approximation, the fact that ^{170}Tm and ^{170}Yb are strongly deformed nuclei, situated well within the region for application of the Nilsson model, makes this β transition an interesting one to study.

All of the directional correlation measurements reported so far, except for some of those of Pfeifer and Runge,[9] are for time-integrated correlations, i.e., the time resolutions of the coincidence circuits used were much longer than 2.3 ns, the mean life of the 2^+ intermediate state. In the work of Pfeifer and Runge, also, the time resolution was never better than 8 ns. There has thus been some question as to whether the values reported so far may not have been attenuated because of interactions between the nuclear moments and atomic fields. Different values obtained by some workers[8,12] for different physical and chemical source environments are an indication that attenuations may not be negligible. In the present work an attempt has been made to determine the true correlation, as it would be without effects of extranuclear interactions, with the help of faster time-spectroscopic techniques. Since the time dependence of attenuation is simpler for a liquid source, some effort was put into developing such a source, with a thin window, for use in the vacuum chamber of the magnetic spectrometer. An extensive discussion of the experiment and its motivation appears elsewhere,[17] and preliminary results have also been reported.[18]

II. ATTENUATED β-γ DIRECTIONAL CORRELATIONS

The directional correlation function $W(\hat{k}_1, \hat{k}_2, t)$ for the cascade $I_i \xrightarrow{R_1} I \xrightarrow{R_2} I_f$, where R_1 and R_2 are emitted in the directions $\hat{k}_1$ and $\hat{k}_2$, respectively,

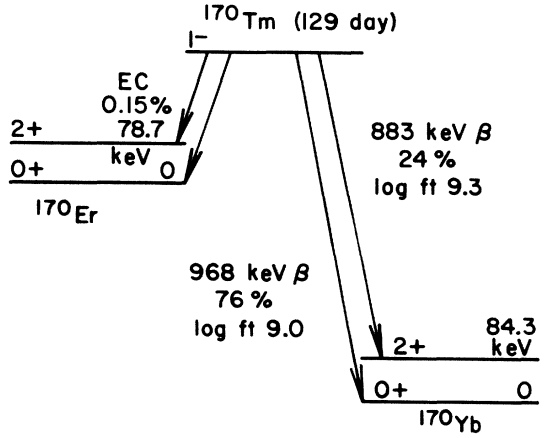

FIG. 1. Decay scheme of ^{170}Tm showing transitions involved in this work.

and R_2 is emitted at a time t after R_1, is in most cases[19] given by the following expression:

$$W(\hat{k}_1, \hat{k}_2, t) = 1 + \sum_k A_k G_k(t) P_k(\cos\theta), \quad (1)$$

where θ is the angle between $\hat{k}_1$ and $\hat{k}_2$, the P_k are Legendre polynomials, $G_k(0) = 1$, and A_k vanishes unless k is even and $2 \leq k \leq \text{Min}(2I, 2L_1, 2L_2)$, with L_1 and L_2 the largest contributing multipoles in R_1 and R_2. It was assumed in this work, as is conventional in the study of nonunique first-forbidden transitions, that terms with k higher than 2 could be neglected. This assumption is supported by the results of Pfeifer and Runge,[9] and of Khayyoom *et al.*,[12] based on measurements at more angles, that the value of the A_4 coefficient was small.

The attenuation function $G_k(t)$ accounts for random changes in nuclear orientation during the time the nucleus spends in the intermediate state. The correlation as given by Eq. (1) will be realized only if the coincidence system used has infinitesimally small resolving time. When either the mean life of the intermediate level, or the time scale for significant change in $G(t)$, is of the same order of magnitude as the experimental width of the time spectrum recorded by the apparatus for prompt coincidences, the quantities in Eq. (1) must be folded with a normalized prompt spectrum. In general, $G_k(t)$ is a complicated function of t, so extraction of the A_k values is not straightforward. As discussed by Abragam and Pound,[20] however, the mechanism of perturbation in a liquid is such that the attenuation function is simply an exponential. The directional correlation function for a liquid source is therefore given by a folded version of Eq. (1) with

$$G_k(t) = \exp(-\mu_k t). \quad (2)$$

III. EXPERIMENTAL ARRANGEMENT AND METHOD

A. Experimental arrangement

The β-γ correlation in ^{170}Tm decay was studied with the double-focusing magnetic spectrometer described by Wohn and Wilkinson.[21,22] Under the conditions of measurement the spectrometer transmission and resolution (not including the effects of energy loss in the source) were each about 1.5%. A liquid source[17] in the form of a chloride in dilute HCl solution, obtained commercially, was used. The thickness of the liquid, in the direction taken by electrons entering the spectrometer, was 2–4 mg/cm^2. The liquid was contained, in that direction, by a thin Mylar film.

Plastic scintillators were used to detect both the focused β rays and the γ rays. Lucite light pipes connected the scintillators to low-noise fast-response photomultiplier tubes, which were magnetically shielded from the spectrometer field. The γ-ray detector was moved back and forth between 90° and 180° positions with respect to the direction of emission of the β rays. A fast-slow coincidence arrangement was used with a commercial time-to-pulse height converter (TPHC), and time spectra were recorded in a multichannel analyzer. While the linear signals from the β-ray detector were unambiguous, some care had to be taken in setting a window on the upper part of the Compton distribution from the 84-keV γ rays of interest, so that they could be distinguished from the K x-rays of ytterbium, which are more numerous, but whose Compton edge is at lower energy. The automated system for recording the spectra and moving the γ-ray detector has been described by Seubert.[23]

B. Method

Time spectra from the TPHC, $F(\theta, t)$, where t is the experimental time delay between the β rays and the γ rays, were recorded for equal lengths of counting time for $\theta = 90°$ and 180°. Random coincidence rates were determined simultaneously, and subtracted channel by channel. Since it has been suggested[24] that internal bremsstrahlung may make substantial contributions to such an experimentally determined anisotropy, its effect was determined in independent measurements[17] and found to be negligible.

The sum $(\frac{2}{3})F(90°, t) + (\frac{1}{3})F(180°, t)$ was then constructed for the data of each run; in this sum the angular dependence is canceled out, leaving the composite spectrum to be a convolution of the prompt curve with the natural exponential decay of the 2^+ level. A prompt curve consisting of two half-Gaussians with exponential wings was fitted to this composite spectrum. This form for the prompt curve was confirmed by direct observation of the prompt spectrum, taken at the same field and with the same window settings, of ^{60}Co β-γ coincidences. The full width at half maximum of the resulting prompt curve was 2.25 ns.

Once the parameters describing the prompt curve, $P(t')$, were determined, the following integral equation[25] was unfolded to determine the coefficient A'_2, the directional correlation coefficient uncorrected for finite solid angle:

$$F(\theta, t) = \int_{-\infty}^{\infty} f(\theta, t') P(t - t')\, dt', \quad (3)$$

where

$$f(\theta, t') = 0, \quad \text{for } t' < 0$$
$$= \lambda e^{-\lambda t'}[1 + A'_2 G_2(t') P_2(\cos\theta)], \quad \text{for } 0 \leq t', \quad (4)$$

TABLE I. Results for the β-γ directional correlation coefficient in ^{170}Tm decay, for total electron energy of 1.50 $m_e c^2$. A_2' is the measured coefficient, uncorrected for finite solid angle, and μ is the coefficient for time-dependent attenuation of the correlation, defined in Eq. (2). After solid-angle correction the resulting correlation coefficient is $A_2 = -0.179 \pm 0.018$.

Run numbers	A_2'	μ (ns)$^{-1}$
1–3	-0.194 ± 0.021	0.510
4–6	-0.121 ± 0.017	0.527
7–9	-0.226 ± 0.031	0.533
10–12	-0.193 ± 0.040	0.565
13–15	-0.131 ± 0.014	0.620
16–18	-0.154 ± 0.021	0.588
19–21	-0.302 ± 0.042	0.539
22–24	-0.120 ± 0.092	0.569
25–27	-0.123 ± 0.061	0.467
Weighted average	-0.155 ± 0.016	0.546

with λ the transition probability for decay of the intermediate state, and with G_2 given by Eq. (2). Acceptable fits were found, confirming the exponential nature assumed for the attenuation.

IV. RESULTS

Results for the directional correlation coefficient, uncorrected for the finite solid angles subtended by the detectors, are given in Table I, together with the values found for μ, the attenuation coefficient. Each run contains data collected over a period of 24 hours, with three measurements of four hours each at 90° and 180°. Corrections for the finite solid angle subtended by the γ-ray detector are standard. Those for the β-ray spectrometer used the method, and the results for this spectrometer, of Wohn.[21,22]

The unperturbed directional correlation coefficient A_2 was determined in this way to have the value -0.179 ± 0.018, for a β-ray energy of 1.50 $m_e c^2$. The average attenuation coefficient, for the sources used in this work, was 0.55 ns^{-1}. This implies that the result of a measurement, with the sources used in this work, with coincidence resolving time much longer than the intermediate level lifetime, would have been $A_2 = -0.08$, in reasonable agreement with many of the A_2 values reported in the literature;[3-7,9-11] but somewhat smaller than the values found by Novey[2] and Ellis.[8] In all of these earlier measurements the resolving time was considerably longer than was used in the present work. In particular, the intermediate-state relaxation time of 1.8 ns found here is consistent with the finding of Pfeifer and Runge,[9] that for the sources used by them the relaxation time was either small compared to 8 ns or long compared to 16 ns; the larger unattenuated A_2 coefficient found here implies that their relaxation time was, like ours, small compared to 8 ns. Even in the most recent published work on this β-γ correlation,[12] it was assumed that there was no attenuation of the correlation in a liquid source, and the resulting value of the A_2 coefficient at $W = 1.5\ m_e c^2$ is only about 40% of the value found here.

It is our conclusion that most previous determinations of the β-γ directional correlation in ^{170}Tm decay have been significantly affected by attenuation during the finite lifetime of the intermediate state, and that the true value of the correlation coefficient is larger than has usually been reported.

V. DISCUSSION

β transitions from 1- to 2+ are first forbidden nonunique, and in lowest order the only contributing matrix elements are $\int \vec{r}$, $\int \vec{\alpha}$, $\int \vec{\sigma} \times \vec{r}$, and $\int B_{ij}$. Since the ^{170}Tm transition involves the change of Nilsson configuration from the neutron orbital [521↓] to the time reverse of the proton orbital [411↓], each of these matrix elements is twice hindered in the asymptotic quantum numbers.[26] Inclusion of the corrections to the lowest order matrix elements involving insertion of additional powers of r^2 does not reduce this asymptotic quantum number hindrance. Only when one reaches, at the level of third-forbidden transitions, operators which can change the component of orbital angular momentum by two units while also flipping the spin, does one find nuclear matrix elements for this transition which are not asymptotically hindered. This is perhaps the reason why this transition has an ft value about 10^3 times greater than do the asymptotically unhindered $\Delta K = 0$ transitions between this same pair of orbitals in odd-mass nuclei in this region of the nuclidic chart.

Results of some preliminary searches for sets of nuclear matrix elements may be found in Ref. 17.

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†Present address: Department of Atomic Energy, College House, Begumpet, Hyderabad-16, India.

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