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MEASUREMENT OF THE ^{171}Tm ISOMERIC LIFETIME AS A TEACHING LABORATORY EXPERIMENT

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Abstract—A teaching experiment is described in which two methods are applied to determine the lifetime of an isomeric state in ^{171m}Tm. One method, a single channel measurement, utilizes a delayed coincidence technique while the second, a multichannel measurement, employs time-to-pulse height conversion. Both serve to illustrate several principles of coincidence and timing measurements and can give results of good accuracy.

1. INTRODUCTION

THE EXPERIMENTAL measurement of the lifetime of an isomeric nuclear state can serve as a useful and interesting illustration of several experimental techniques. The measurements to be described here have been incorporated into a senior-first year graduate course in nuclear measurements at The University of Michigan. Our experience has been that the experiment not only serves as a useful teaching tool, but can also yield results which are comparable in accuracy to published values for an isomeric state lifetime in ^{171}Tm.

2. SOURCE AND DECAY SCHEME

The decay scheme for ^{171}Tm is shown in Fig. 1. The level at 0·425 MeV has a halflife of about 2·6 μseconds and is the isomeric state of interest in this measurement. All other excited states of the nucleus have lifetimes which are much smaller than this figure. As illustrated in Fig. 1, the isomeric state can be populated through the beta decay of ^{171}Er, which in turn can be produced through neutron irradiation of natural erbium metal.

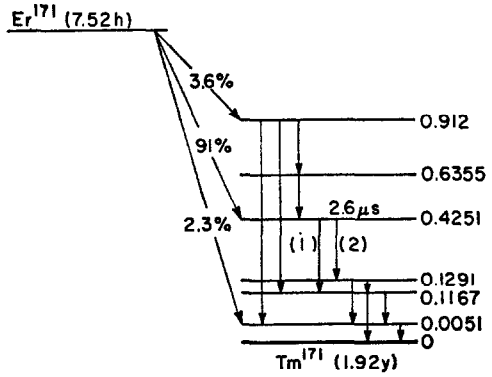

FIG. 1.—Level scheme of ^{171}Tm from LEDERER, HOLLANDER and PERLMAN (1968) showing most prominent transitions only.

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Several factors have led to the choice of the particular decay scheme and isomeric state for examination. First of all, the magnitude of the isomeric mean lifetime is about right, in that it is neither too small for conventional instrumentation time resolution nor too large for convenient application of the measurement techniques. The isomeric state is populated in 91 per cent of the decays of ^{171}Er and gives rise to gamma rays which are of convenient energy and can be distinguished from other de-excitation gamma rays.

Natural erbium metal consists of six stable isotopes. The abundance of ^{170}Er is 14·8 per cent. Its thermal neutron capture cross section is about 9 barn, sufficient to insure adequate activation in reactor fluxes. Only three of the remaining stable isotopes of erbium produce a radioactive isotope of appreciable halflife after thermal neutron capture. ^{162}Er and ^{164}Er have comparatively low thermal neutron capture cross sections (2·0 and 1·7 barn respectively) and are present with such small abundance in natural erbium (0·13 per cent and 1·56 per cent) that the resultant activities are negligible compared with ^{170}Er activation. ^{168}Er is present to 27 per cent abundance and has a capture cross section of 2 barn. However, the resulting ^{169}Er beta activity has an endpoint energy of only 0·34 MeV, compared with the endpoint energy of 1·04 MeV for ^{171}Er. As a result, this competing activity can be easily discriminated on a pulse height basis in the beta detector.

Erbium can be obtained in the form of metallic turnings through the American Potash & Chemical Corporation at a nominal cost. If reactor neutron fluxes are available, only subgram quantities are required for the experiment.

3. EXPERIMENTAL CONSIDERATIONS

Two independent measurement techniques have been used to record the isomeric decay. Both are based on multiple measurements of the time interval between detection of a beta particle from decay of ^{171}Er and subsequent detection of the de-excitation gamma ray from the isomeric state formed in the same decay. The first method employs the delayed coincidence technique and is essentially a single channel measurement, while the second involves time-to-pulse height conversion and is a multichannel method.

The beta particles emitted by ^{171}Er in the experiment were detected by a $\frac{1}{4}$ in. thich anthracene crystal scintillation counter, whereas the gammas emitted by the isomer were detected by a 2 × 2 in. NaI(Tl) scintillator. Since it is desirable that one detector should respond only to gamma rays and the other should detect only betas, the use of the anthracene and NaI crystal scintillation detectors is a reasonable choice. As shown in Fig. 2, a 1·7 mm thick aluminum sheet was placed between the source and NaI detector, insuring that no beta particles can penetrate the crystal aluminum cover, while the gamma rays of interest are not appreciably attenuated.

The thickness of the anthracene crystal is such that its efficiency for detection of gamma rays is small, and those interactions which do occur can be largely discarded by pulse height discrimination. The crystal was mounted on a DuMont 6292 photomultiplier tube behind a .0013 cm aluminum foil light cover. A pulse height spectrum of the activated erbium sample is shown in Fig. 3. The SCA following this detector was set with an integral mode discrimination point at about 30 per cent of the maximum size pulses to suppress both the gamma ray interactions and the contributions of the ^{169}Er beta activity.

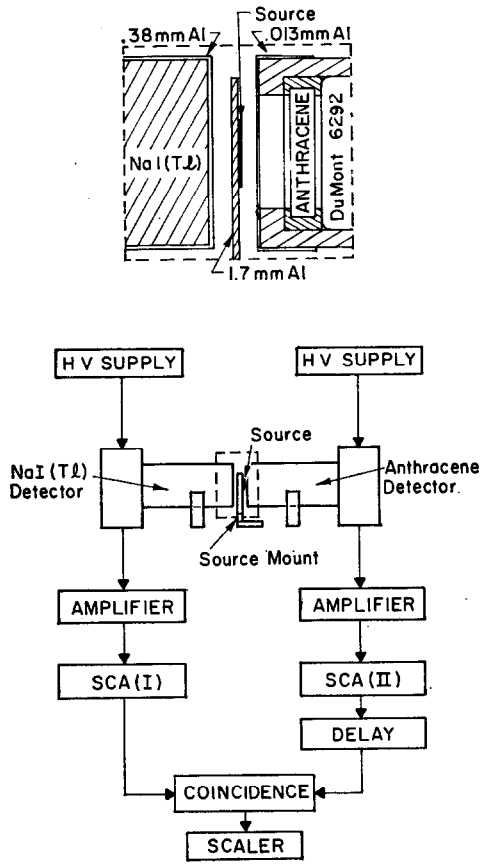

FIG. 2.—Block diagram of the delayed coincidence technique.

The NaI detector used is a commercially available device and needed no modifications in this experiment. The intrinsic peak efficiency for 0·3 MeV gamma rays is about 40 per cent. The observed pulse height spectrum from the erbium sample is shown in Fig. 4. The large peak indicated by the ΔE window contains the unresolved 0·296 and 0·308 MeV photopeaks from the two de-excitation gamma rays which originate from the isomeric level. The SCA following this detector was set with the indicated differential window to exclude other gamma rays as much as possible. There will, however, always be some contribution from gamma rays which do not involve the isomeric state through inscatter and Compton continua from higher energy peaks. Since these involve levels whose lifetime is very small, they will occur in coincidence with the beta particle and contribute to a prompt coincidence peak in the time spectrum.

3.1 *Method A—delayed coincidence*

The first technique used to determine the decay characteristics of the isomeric level is outlined in Fig. 2. After the pulse height selection described above, signals from the beta and gamma ray detectors are routed to a coincident circuit with a fixed 150 nanosecond resolving time. A variable delay is inserted into the beta ray branch

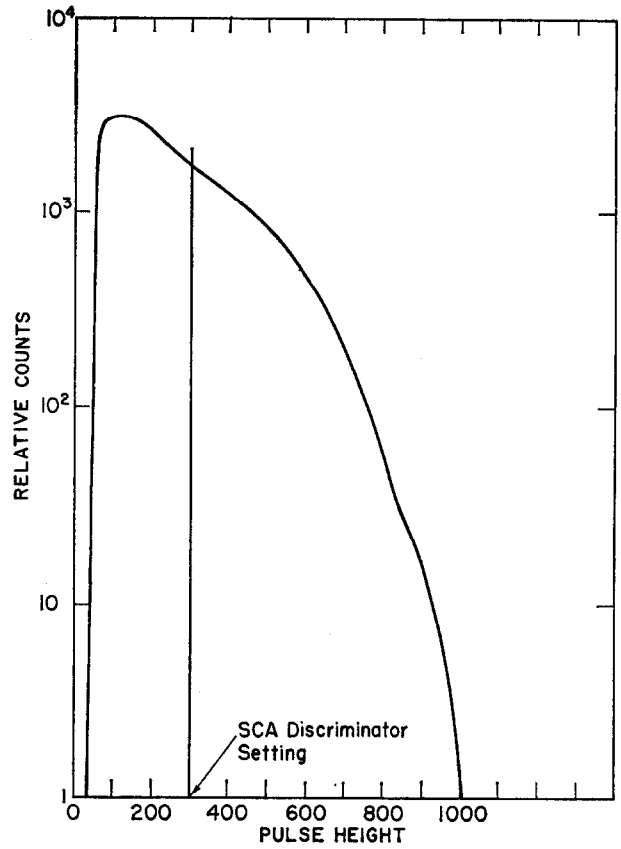

FIG. 3.—Differential pulse height spectrum from the anthracene scintillator.

through use of a triggered delay pulser. Measurements were made of the counting rate at successive settings of the delay differing by 300 nanoseconds.

Figure 5 shows the results of a typical measurement. Counting times were 15 min for each point and the data have been corrected for source decay between counting intervals. The chance coincidence contribution has also been subtracted and can easily be obtained as the total coincidence count rate at very large delay times (>100 μseconds).

3.2 *Method B—time-to-pulse-height conversion*

The second method is illustrated in Fig. 6. In this case, each beta detection serves as a START signal for a time-amplitude converter (TAC). The STOP pulses for the converter consist of those gamma rays which pass the single channel analyzer following the sodium iodide crystal. In this way, each detected beta particle will give rise to an output pulse from the TAC as long as a pulse arrives at the STOP input within the converter time range. In practice, only a small fraction of all beta signals will be followed by an appropriate STOP signal, since the probability of detection of the gamma ray corresponding to any given beta event is small. In those cases in which a STOP pulse does arrive within the time range of the TAC, an output pulse is produced whose amplitude is proportional to the time interval between START and STOP.

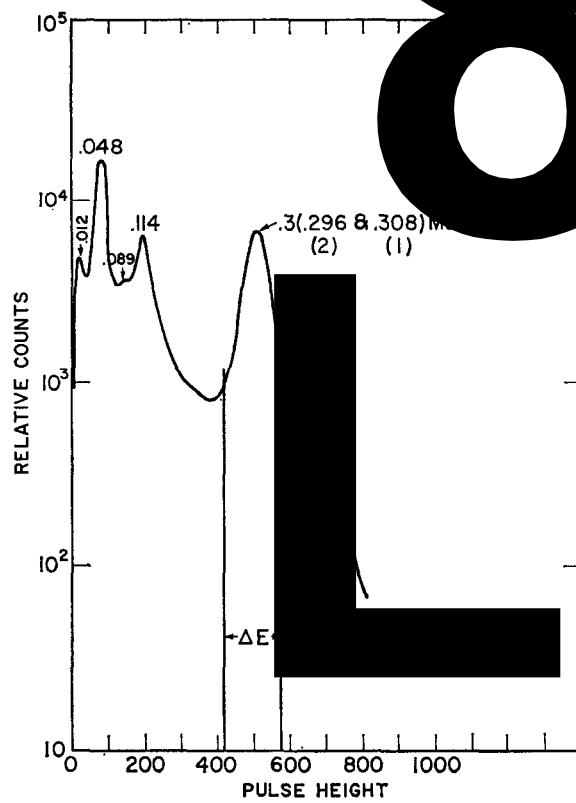

FIG. 4.—Differential pulse height spectrum from the sodium iodide scintillator.

If we are detecting only gamma rays from the isomeric state, then the cumulative distribution of these intervals should be a pure exponential whose decay characteristics are those of the isomeric level. The remainder of the apparatus is similar to that used in the delayed coincidence method. The triggered pulser simply serves in this case as a convenient means of introducing variable delay into one branch for initial adjustment purposes, and is not varied during a measurement. It is shown in the beta ray branch to indicate the case in which "zero time" or the prompt coincidence peak will appear downscale on the MCA.

The multichannel analyzer must first be calibrated in terms of a corresponding time scale. This can be accomplished by introducing a fixed delay between START and STOP pulses. The output of either single channel analyzer can be split and sent down both branches of the circuit and a fixed delay introduced by placing the triggered pulser in the STOP branch. In this way, all events will accumulate in nearly the same channel. The procedure can then be repeated for a variety of fixed delays and a calibration made of delay time versus channel number. A convenient means of measuring the delay time is to trigger an oscilloscope with the START pulse and display the STOP pulse on the sweep. Differences in delay time can then be measured by noting the apparent movement of the STOP pulse along the oscilloscope display. The time scale of the oscilloscope can, in turn, be conveniently calibrated to within power line frequency precision using conventional nuclear counting equipment.

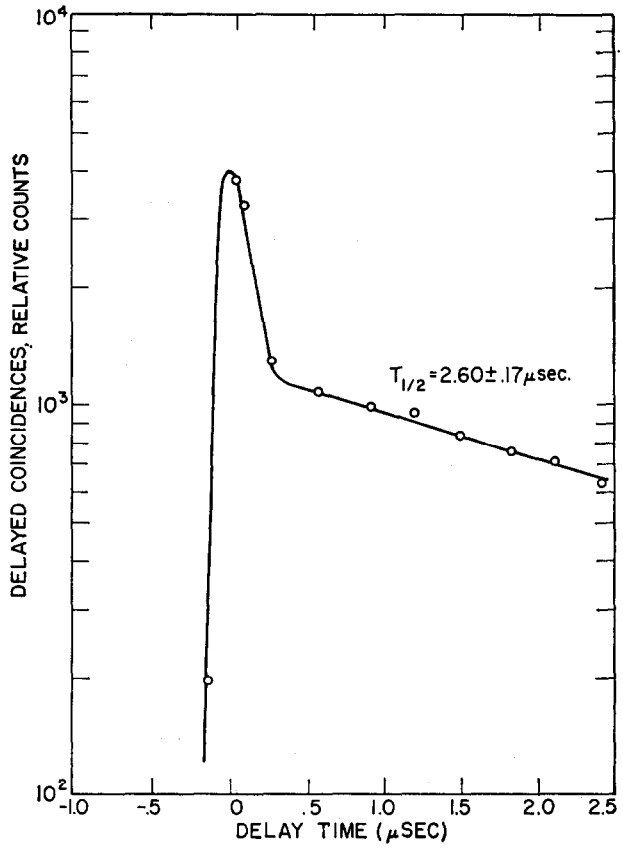

FIG. 5.—Results of the delayed coincidence measurements.

The output of a fixed frequency pulser with period of the same order as the time interval of interest (~1 MHz) is simultaneously displayed on the oscilloscope and counted by a fast scaler. The observed pulse spacing can then be calibrated against the known period as measured by the scaler and timer (usually line frequency synchronized). Any non-linearities across the oscilloscope screen can also be noted.

A set of data are shown in Fig. 7 which were generated using the multi-channel method. Data were accumulated for 60 min with the delay adjusted to give "zero time" near the low pulse height end of the analyzer range. As before, there is a contribution from random or chance coincidences which can be measured separately by increasing the delay beyond the range of the MCA (moving "zero time" off the high pulse height end). Under these conditions there can be no true coincidences and the recorded spectrum is due entirely to chance coincidences. This spectrum also is a direct measure of the differential time linearity of the system. If the TAC and MCA are completely linear, the chance spectrum should be flat. Any deviations should be consistent with the results of the integral time calibration described earlier. The data in Fig. 7 has been corrected by subtracting chance coincidences for identical single counting rates and analysis time, and by correcting for deviations from exact linearity of the time scale. In making the latter correction, it should be remembered that not only must

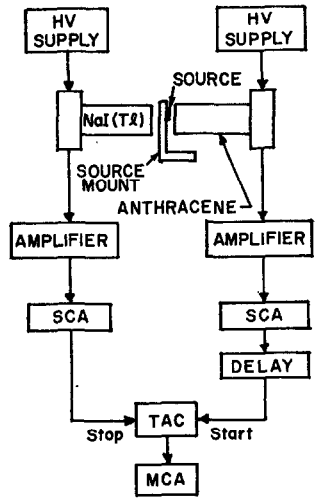

FIG. 6.—Block diagram of the time–amplitude conversion technique.

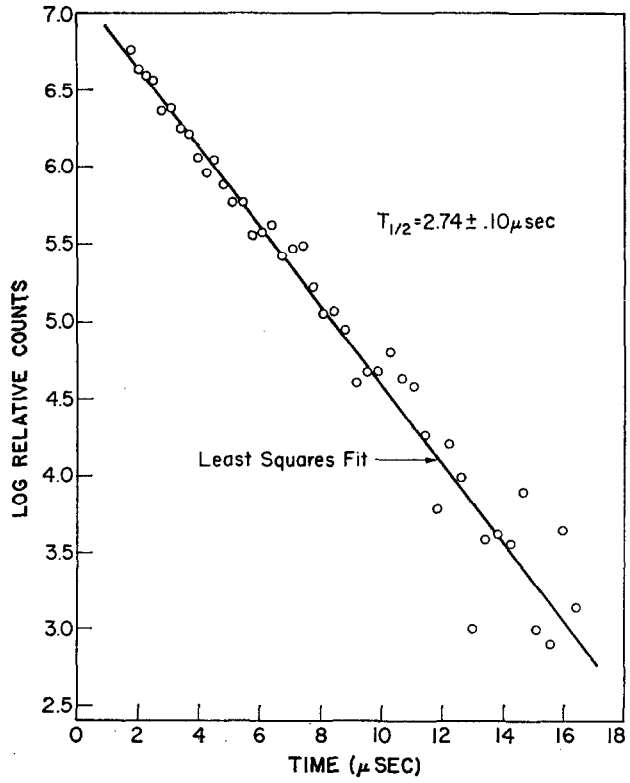

FIG. 7.—Corrected time spectrum from the time–amplitude conversion measurements.

the channel number be converted to corresponding time, but also the number of counts per channel must be multiplied by the appropriate factor:

$$N(t) = N(x) \cdot \frac{1}{\Delta t_x}$$

where Δt_x is the correct time interval corresponding to channel number x.

4. NUMERICAL RESULTS

The slope taken from Fig. 5 gave a value of the isomeric halflife of $2{\cdot}60 \pm 0{\cdot}17$ μsec. The probable error is a graphical estimate of the slope variation consistent with the data points shown. The multichannel data of Fig. 7 were fitted with a least square routine which gave a value and probable error for the halflife of $2{\cdot}74 \pm 0{\cdot}10$ μsec. No attempt has been made to carefully evaluate possible systematic errors in these results. The statistical errors could likely be reduced by optimizing experimental conditions and using longer counting times.

Four measurements are referenced in a recent compilation (LEDERER, HOLLANDER, and PERLMAN, 1968), of which the most recent gave a value of $2{\cdot}59 \pm 0{\cdot}03$ μsec (CRANSTON, BUNKER and STARNER, 1958). This measurement was made using time-amplitude conversion and multichannel recording (Method B), while the previous measurements used delayed coincidence (Method A).

5. SIGNAL AND NOISE CONSIDERATIONS

Both methods of measuring the coincidence decay curve are amenable to the same analysis regarding signal and chance coincidence rates. In the following, let τ represent either the resolving time of the coincidence circuit in Method A or the time width of a specific channel in Method B. If we neglect background not associated with the erbium sample (a very good assumption here), the singles counting rate from the beta branch can be written:

$$R_\beta = S\varepsilon_\beta$$

where S is the source activity and ε_β is the overall probability per source disintegration that a pulse be generated by the beta signal SCA. Similarly

$$R_\gamma = S\varepsilon_\gamma$$

for the singles rate in the gamma ray branch. The true coincidence rate arising from detection of beta particles and de-excitation gamma ray from the *same* nuclear event in a time interval τ after a delay time T is:

$$R_t = Sf\varepsilon_\beta\alpha_\beta\varepsilon_\gamma\alpha_\gamma$$

where f = probability that a given isomeric level will decay within the interval τ following a lifetime T.

α_β = fraction of all accepted events from the beta detector which are actually associated with population of the isomeric level.

α_γ = fraction of all accepted events from the gamma ray detector which are associated with decay of the isomeric level.

Care in setting the SCA's will insure that α_β and α_γ are close to unity. To evaluate the fraction f:

$$f = \int_T^{T+\tau} \lambda e^{-\lambda t}\, dt = e^{-\lambda T}(1 - e^{-\lambda\tau}) \cong \lambda\tau e^{-\lambda T}$$

where λ is the isomeric level decay constant.

The true coincidence rate becomes:

$$R_t = \lambda S\tau\varepsilon_\beta\varepsilon_\gamma\alpha_\beta\alpha_\gamma e^{-\lambda T}.$$

The detection rate for chance coincidences (detection of radiation from different nuclear events within the time interval) is given by:

$$R_{ch} = 2\tau R_\beta R_\gamma = 2\tau S^2\varepsilon_\beta\varepsilon_\gamma$$

and the ratio

$$\frac{R_t}{R_{ch}} = \frac{\lambda\alpha_\beta\alpha_\gamma e^{-\lambda T}}{2S}.$$

It should be noted that, while the true coincident rate varies linearly with source activity, the true-to-chance ratio varies inversely. Consequently, the experiment should be conducted with as low a source activity as is consistent with data statistics. Since ε_β and ε_γ contribute linearly to the true rate but do not enter the ratio, data rates can be increased by moving the detectors as close as possible to the source without adversely affecting the true-to-chance ratio. The same behavior holds for the resolving time (or channel width) τ, so that its value should not be too small compared with the isomeric decay time. Some of the statistical fluctuations shown in Fig. 7 could have been reduced by using a more compressed time scale without affecting the true-to-chance ratio. Making α_β and α_γ as close as possible to unity will enhance the ratio, but too stringent pulse height selection will decrease ε_β and ε_γ, and hence the data rate. Finally, it should be noted that the ratio varies as λ, so that the experiment is best suited for the measurement of lifetimes that are as small as possible consistent with instrumental time resolution. The data shown in the examples gave true-to-chance ratios of about 10:1 for small values of T.

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