Lifetimes of 4+ and 2+ States in the Rotational Nuclei Dy^{160}, Dy^{162}, Er^{166}, Er^{168}, and Hf^{180}†

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Lifetimes of the 2+ and 4+ states of the ground-state rotational band were measured for five even-even rare-earth nuclei using delayed coincidence techniques. The half-lives obtained are presented in the following table in units of 10^{-10} sec.

Nucleus	2+ state	4+ state
Dy^{160}	19.9±0.5	1.07±0.15
Dy^{162}	22.5±0.7	1.32±0.08
Er^{166}	18.3±0.6	1.20±0.08
Er^{168}	19.0±0.6	1.21±0.08
Hf^{180}	15.3±0.5	0.75±0.10

The ratios $B(E2; 4 \rightarrow 2)/B(E2; 2 \rightarrow 0)$ are calculated from these lifetimes using theoretical values for the internal conversion coefficients. In all cases this ratio is in excellent agreement with the value 10/7 predicted by the strong coupling model for rotational nuclei.

A measurement of the lifetime of the 2.50-MeV 4+ state of Ni^{60} is also reported. A limit of $\tau_m < 5 \times 10^{-12}$ sec was obtained for this state.

I. INTRODUCTION

STRONGLY deformed nuclei in the rare-earth region are known to have low-lying levels of the spin sequence 0+, 2+, 4+, $\cdots$, characteristic of rotational excitation. The energies of the levels have approximately the $I(I+1)$ dependence of the strong-coupling model.[1] For the region of mass numbers 160–180, the energy ratio of the 4+ level to the 2+ level agrees with the predicted value of 3.33 generally to better than 2%. The model also predicts a definite ratio between the reduced transition probabilities of the $4+ \rightarrow 2+$ and $2+ \rightarrow 0+$ electric quadrupole transitions. In the strong-coupling limit the ratio of the reduced transition probabilities, $B(E2; 4 \rightarrow 2)/B(E2; 2 \rightarrow 0)$, is equal to 10/7. Furthermore, it can be shown that, consistent with the observed deviations in the energies of the ground-state band, the commonly considered perturbations should not produce a change of more than a few percent in the value of this ratio. Therefore, the predictions of the present theory for this ratio are very strong and depend essentially only upon the validity of the gross features of the model.

The lifetimes of many 2+ rotational states have already been measured by Coulomb excitation or by the delayed coincidence method. The number of 4+ state lifetimes measured is very much smaller because these are of the order of 10^{-10} sec and present an experimental problem of much greater complexity. In the present work[2] we have attempted to determine with some accuracy the 4+ state lifetimes of Dy^{162}, Er^{166}, Er^{168}, and Hf^{180}. We also remeasured the lifetimes of the 2+ states of these nuclei with a view to reducing the errors.

The choice of these particular nuclei for these measurements was dictated primarily by the relative simplicity of the decay schemes involved and the ease of production of the parent nuclei.

After completion of the measurements on the above nuclei, it came to our attention that there is an apparent discrepancy between the model prediction and the experimental ratio of $B(E2)$ values derived from recently published data for the 4+ and 2+ states in Dy^{160}. We were therefore prompted to remeasure these lifetimes in Dy^{160}, even though the decay scheme is complicated and the precision our method affords is poorer than in the other cases. A review of the published data on this nucleus is presented below.

We have also attempted to measure the lifetime of the 4+ state of Ni^{60}. Although this nucleus does not exhibit a rotational spectrum, the results are presented in this paper because the experimental technique is similar to that used for the Hf^{180} measurements. The results are presented in Appendix II.

II. EXPERIMENTAL EQUIPMENT

The lifetime measurements were made by the delayed coincidence method using a 6BN6 time-to-pulse-height converter. The associated circuitry shown in the block

† Work performed under the auspices of the U. S. Atomic Energy Commission.

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[1] A. Bohr, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **26**, No. 14 (1952); A. Bohr and B. R. Mottelson, *ibid.* **27**, No. 16 (1953).

[2] Some of our results have previously been published in abstract form as follows: Hf^{180}, A. C. Li and A. Schwarzschild, *Electromagnetic Lifetimes and Properties of Nuclear States* (Nuclear Science Series Report Number 37), National Academy of Sciences, National Research Council Publication 974, Washington, D.C., 1962, p. 84; Dy^{162} and Er^{168}, Bull. Am. Phys. Soc. **7**, 359 (1962).

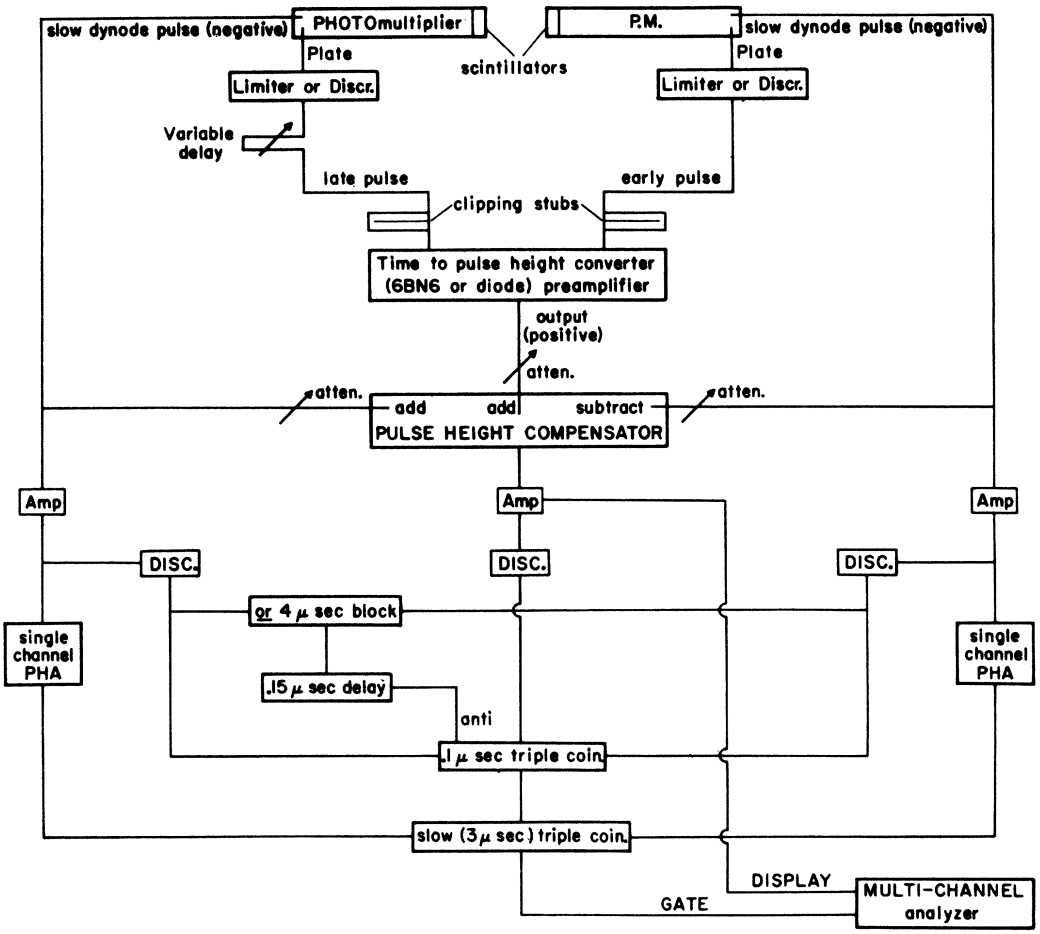

FIG. 1. Block diagram of apparatus used in lifetime measurements.

diagram of Fig. 1 is similar to that described by Green and Bell.[3] Some of the details of our particular apparatus[4] and a general discussion of the technique[5] are presented in previous publications. Using 56AVP photomultipliers and two 1-in.×1-in. Nash-Thompson Naton 136 plastic scintillators, the prompt resolution curve obtained for Co^{60} had a width at half-maximum of 1/3 nsec. The sides of the prompt curve had exponential slopes which decreased by a factor of two in 4×10^{-11} sec.

Time calibrations were made by observing the shift of the time spectrum centroid as a function of inserted delays. For the 4+ state lifetime measurements, the variable delay line consisted of two 125-Ω air core "trombones" for which the signal propagation velocity is c to within 1%.[4] For the longer 2+ state lifetimes, pieces of 125-Ω RG63/U cables differing in length by 1 ft were used in series with three trombones of combined length equivalent to 5 nsec. Points on the calibration curve were obtained alternately by varying the trombone delays and by changing the cable lengths. We found no perceptible difference between one foot of our cable and 1.25-nsec delay through the trombones. Figure 2 shows two typical calibration curves for the two sets of measurements.

All the lifetimes were determined from the slopes of the respective time spectra, with the exception of that of the Hf^{180} 4+ state. The Hf^{180} 4+ state has a half-life about 30% shorter than the other 4+ states, and therefore the centroid method of analysis was required. The relative merits of the "slope method" and the "centroid method" as well as sources of systematic errors have been discussed in some detail in an earlier paper.[5] The present experimental apparatus also includes the auxiliary equipment described in that paper, namely, a block or antipulse pile-up circuit and a pulse-height compensator, which reduces the effect of apparent time shift with pulse amplitude.

The measurements on Dy^{160} were performed some

[3] R. E. Green and R. E. Bell, Nucl. Instr. Methods **3**, 127 (1958).
[4] J. V. Kane, R. E. Pixley, R. B. Schwartz, and A. Schwarzschild, Phys. Rev. **120**, 162 (1960).
[5] A. Schwarzschild in *Electromagnetic Lifetimes and Properties of Nuclear States* (Nuclear Science Series Report Number 37), National Academy of Sciences, National Research Council Publication 974, Washington, D. C., 1962. Also, (to be published).

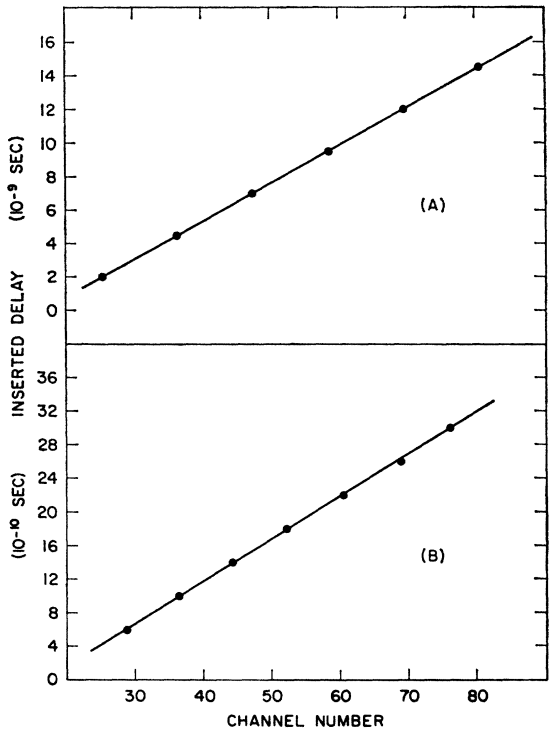

FIG. 2. Calibration curves for the measurements of the 2+ (*A*) and 4+ (*B*) state lifetimes.

time after those of the other nuclei. Different electronic equipment was used for this case and it is described below.

III. Dy^{162}

The 68-min isomer of Ho^{162} was made by the $Tb^{159}(\alpha,n)$ Ho^{162m} reaction. The decay scheme of Ho^{162m} to Dy^{162} shown in Fig. 3 does not include a large number of weak transitions which have been reported.[6,7] In this

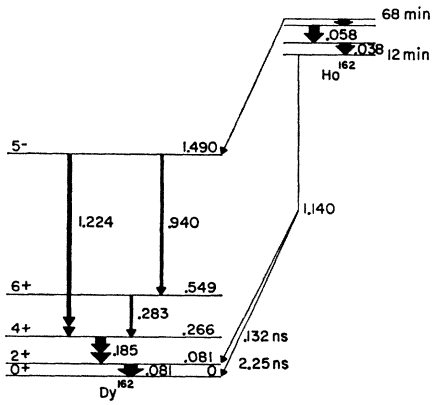

FIG. 3. Decay scheme of Ho^{162m}. Lifetimes shown are the half-lives of the respective levels. (See reference 5.)

[6] M. Jørgensen, O. B. Nielsen, and O. Skilbreid, Nucl. Phys. 24, 443 (1961).
[7] B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. 123, 1758 (1961).

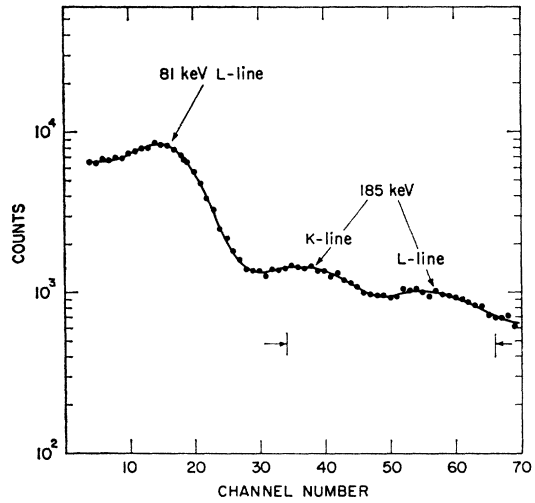

FIG. 4. Singles electron spectrum of Ho^{162m}, using a plastic scintillation detector. The energy selection channel indicated by arrows is that used in the 4+ state lifetime measurement.

figure as in those of other decay schemes presented, the heaviness of the arrow line is proportional to the intensity of the transition; double-headed arrows represent transitions selected for the 4+ state lifetime measurements. No special designation is used for the 2+ state measurements, because there the selection is generally obvious and not so critical.

The source was viewed by a γ-ray counter and an electron counter, which were both Naton 136 plastic scintillators having dimensions 1 in. thick $\times$3/4-in. diameter and 1 mm thick $\times$7-mm diameter, respectively. Absorbers of lead and copper were placed in front of the γ counter to stop electrons and positrons. Be-

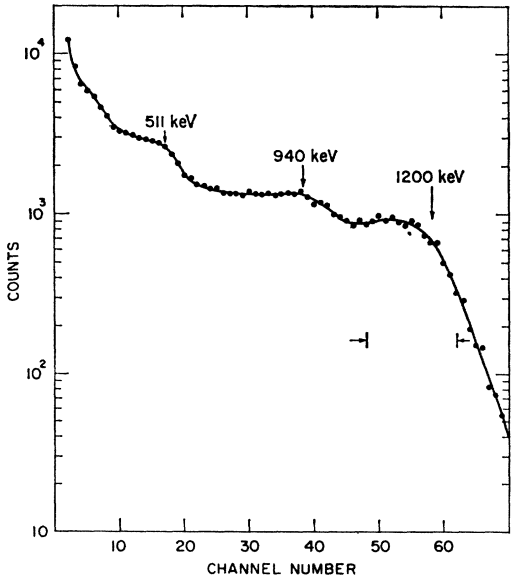

FIG. 5. Singles γ-ray spectrum of Ho^{162m} in a plastic scintillator, and energy selection channel for the 4+ state lifetime determination.

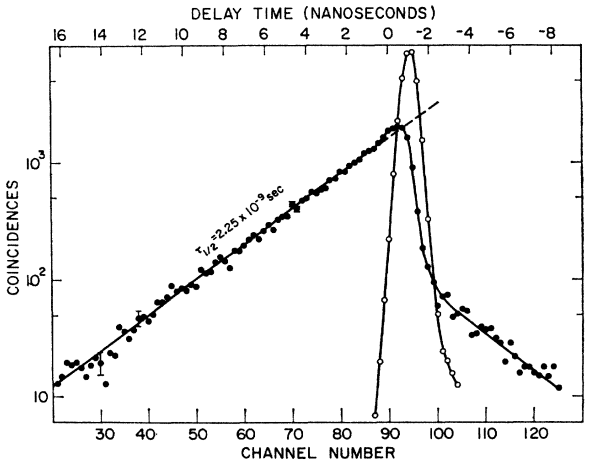

FIG. 6. Time spectrum of coincidences between the 81-keV transition and all preceding γ rays, which gives the Dy^{162} 2+ state half-life. In this figure and all following figures showing time spectra the open circled curves indicate the response of the system to prompt radiation.

tween the source and the electron detector were a piece of 1-mil Mylar covering the source, and a layer of aluminum $\sim 200\ \mu g/cm^2$ thick which covered the scintillator and served as a light reflector. This was the arrangement used for all the lifetime measurements except that of the 4+ states of Hf^{180} and Dy^{160}. Again except for the Hf^{180} measurement, coincidences between the β ray

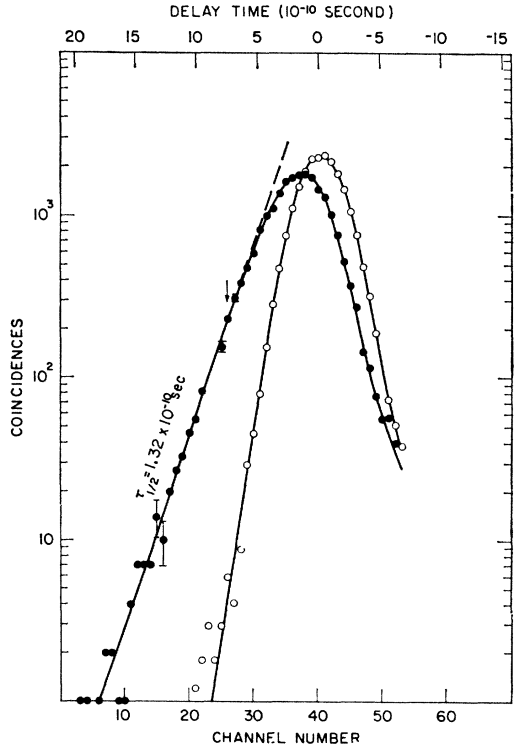

FIG. 7. Time spectrum of 1.224–0.185 MeV coincidences, giving the 4+ state half-life in Dy^{162}.

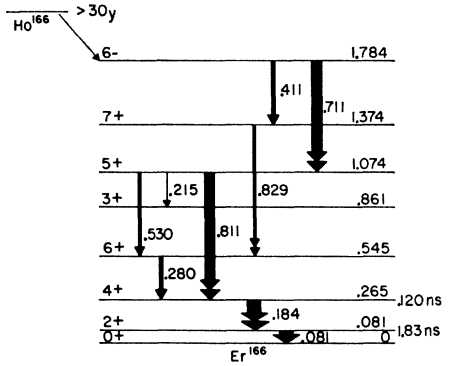

FIG. 8. Decay scheme of the long-lived (>30 yr) Ho^{166}. (See reference 8.)

and the 1.17- or 1.33-MeV γ rays of Co^{60} were used to obtain the prompt spectrum for comparison.

Figures 4 and 5 show the singles spectra of Dy^{162} in the respective counters. The 2+ state half-life was measured by channeling on the L-conversion line of the 81-keV transition in the electron spectrum, and on all the preceding radiation in the γ spectrum. Figure 6 shows the result obtained. The small prompt component evident is to be expected because in the β channel there are some of the electrons from the conversion of the 185-keV transition, some positrons, and some γ rays for which the efficiency of detection is small but not completely absent. The "tail" on the side of negative delay time is not understood from our present knowledge of the decay scheme. It seems to be associated with the 68-min Ho^{162} activity in that it maintains its relative proportion to the rest of the time spectrum as the source decays. Its presence is approximately unaffected by the exact position of the energy selection channel within

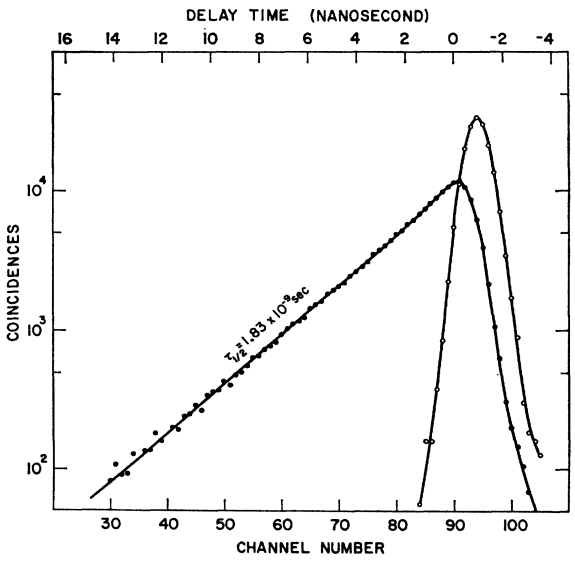

FIG. 9. Time spectrum of coincidences between the 81-keV transition and all preceding γ rays, giving the half-life of the 2+ state in Er^{166}.

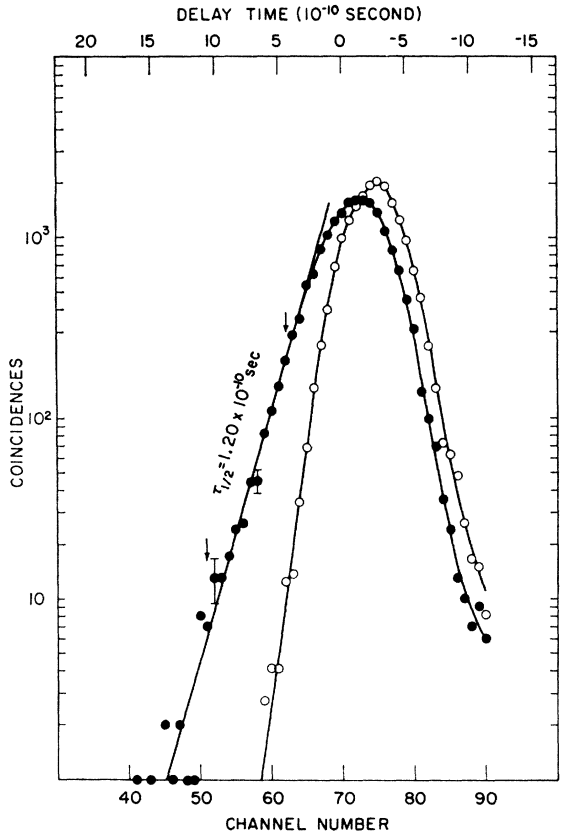

FIG. 10. Time spectrum of coincidences between the 184-keV transition and γ rays of 700–800 keV, from which the Er^{166} 4+ state half-life is obtained.

the range corresponding to 400–1000 keV γ rays. Absorbers sufficient to suppress all the electrons giving rise to the true decay curve also leave this "tail" unaltered. It appears to be produced by γ-γ coincidence, with the late γ ray having quite high energy. Although more work is required to clarify the situation, determination of the 2+ state lifetime does not depend on it. The half-life found for the 2+ state is $(2.25\pm0.07)\times10^{-9}$ sec.

The errors assigned to all the lifetimes reported in the present work are essentially estimates of possible systematic errors. The actual statistical uncertainties are generally smaller than the quoted errors.

The pulse-height regions indicated by arrows in Figs. 4 and 5 are those selected for the 4+ state measurement. The time spectrum obtained is shown in Fig. 7. A least-squares fit made over the entire wing of the spectrum below the point indicated by the arrow yielded a half-life of $(1.32\pm0.08)\times10^{-10}$ sec.

IV. Er^{166}

Figure 8 shows only those levels and transitions in the decay scheme[8] of the long-lived (>30 yr) isomer of

[8] C. J. Gallagher, O. B. Nielsen, O. Skilbreid, and A. W. Sunyar (private communication).

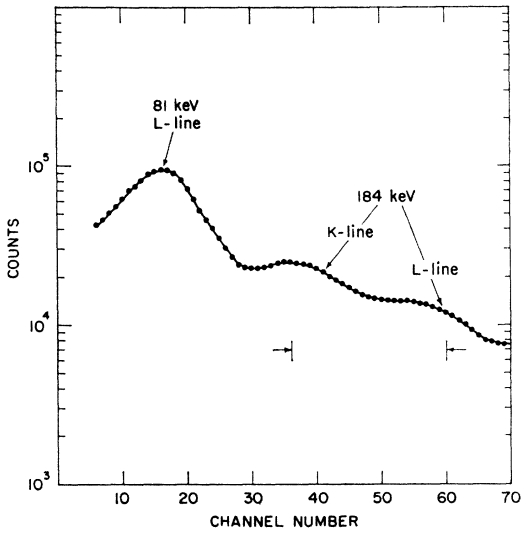

FIG. 11. Singles spectrum of Ho^{166} in the β-ray counter, with channel used in the 4+ state measurement.

Ho^{166} which are pertinent to our measurements. The 2+ state half-life was determined by observing the delayed coincidence between the L-conversion line of the 81-keV transition and γ rays 180 keV and above. Different settings of the γ-ray channel gave the same value of the half-life, which the time spectrum shown in Fig. 9 indicates to be (1.83 ± 0.06) nsec.

The 4+ state lifetime was measured from the coincidence of the conversion electrons of the 184-keV transition and γ rays between 700 and 800 keV. Figure 10 shows the time spectrum. Pulse-height spectra observed in both scintillators are given in Figs. 11 and 12. As can be seen from Fig. 12, the high-energy γ rays are poorly resolved from each other, so that the channel intended

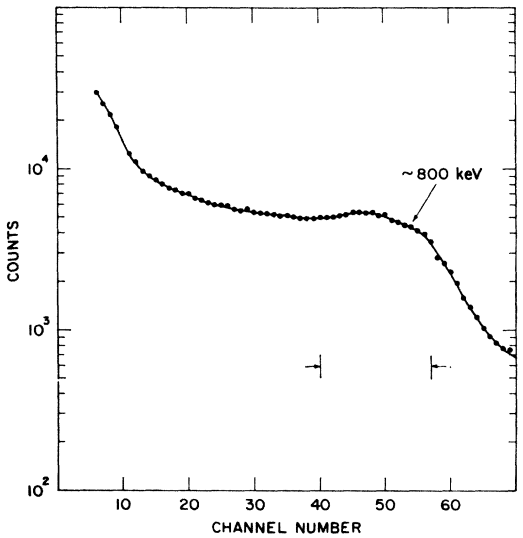

FIG. 12. Ho^{166} singles γ-ray spectrum and channel used in the 4+ state measurement.

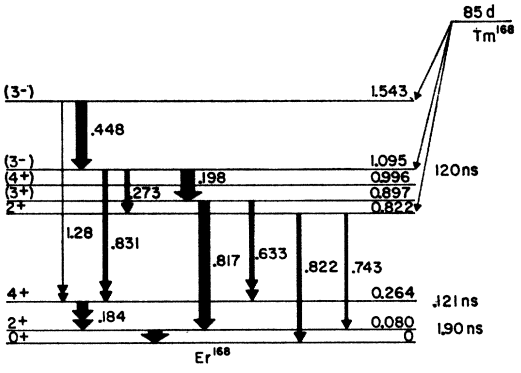

FIG. 13. Decay scheme of Tm^{168} (see reference 10).

to select the 811-keV transition will include the 829-keV and 711-keV transitions as well. Although the 829-keV γ ray does not go directly to the 4+ state, the contribution of coincidences with it to the slope of the time spectrum will reflect only the 4+ lifetime since the 6+ state is expected to be shorter lived by nearly an order of magnitude. The 711-keV transition populates the 4+ state through a 5+ level. From the relative intensities of the transitions depopulating the 5+ level, it can be inferred that the lifetime of this state must be very short. Assuming that the enhancement factors for transitions in the $K=2$ band and in the $K=0$ band are not very different, the 215-keV $E2$ transition between members of the $K=2$ band should go at least as fast as the 184-keV $E2$ transition between members of the $K=0$ band. The fact that the 811-keV transition is many times more intense than the 215-keV transition suggests that the 5+ state is much shorter lived than the 4+ state in question. Apart from such arguments from systematics, a limit of $\leq 6\times10^{-11}$ sec was obtained for the 5+ state half-life from a delayed coincidence experiment between the 711-keV and 811-keV γ rays. To show that even a 6×10^{-11}-sec half-life in the 5+ level would not seriously disturb our lifetime determination, we extended the analysis of Newton[9] to construct a theoretical time spectrum involving two lifetimes in cascade. Taking $\tau_{1/2}(4+)$ as that given by Fig. 10, we constructed a theoretical time spectrum letting $\tau_{1/2}(5+)$ be equal to $\frac{1}{2}\tau_{1/2}(4+)$. Doing a least-squares fit on this constructed spectrum as if only a single lifetime were involved gave a $\tau_{1/2}$ which differed by less than 3% from that assumed for the 4+ lifetime. This discrepancy, if present, is well within the limits of our assigned value of $(1.20\pm0.08)\times10^{-10}$ sec for the 4+ state half-life.

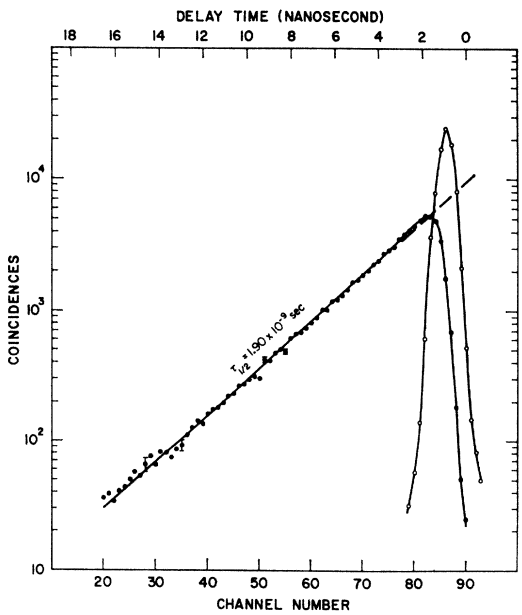

FIG. 14. Time spectrum of coincidences between the 80-keV transition and 550–800 keV γ rays. This gives the half-life of the 2+ state in Er^{168}.

V. Er^{168}

The source of 85-day Tm^{168} was made by (α,n) reaction from Ho^{165}. Separation of the thulium activity from all other rare earths was effected by the ion-exchange method. The source was aged to let the 9.6-day Tm^{167} die out relative to the Tm^{168}.

The Tm^{168} decay scheme[10] is shown in Fig. 13. With exception of the 1.28-MeV γ ray feeding the 4+ level, all transitions of intensity 5% or less have been omitted. For the 2+ state lifetime measurement, one channel was set on the L-line of the 80-keV transition, while the other channel accepted the Compton spectrum corre-

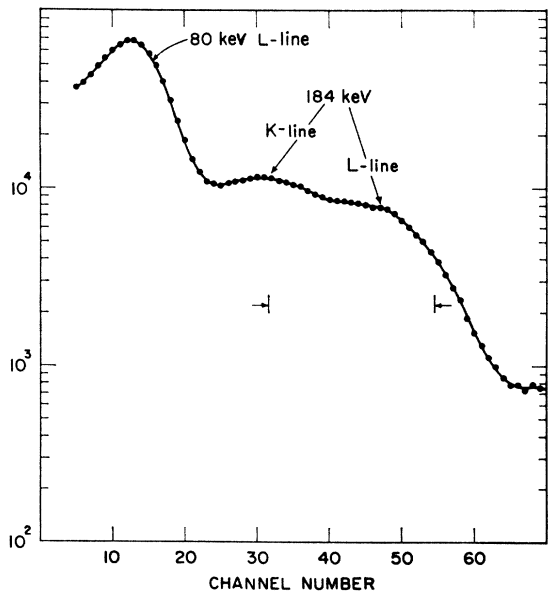

FIG. 15. Singles β-ray spectrum of Tm^{168} and channel used in the 4+ state lifetime determination.

[9] T. D. Newton, Phys. Rev. **78**, 490 (1950).
[10] K. P. Jacob, J. W. Mihelich, and B. Harmatz, Phys. Rev. **117**, 1102 (1960).

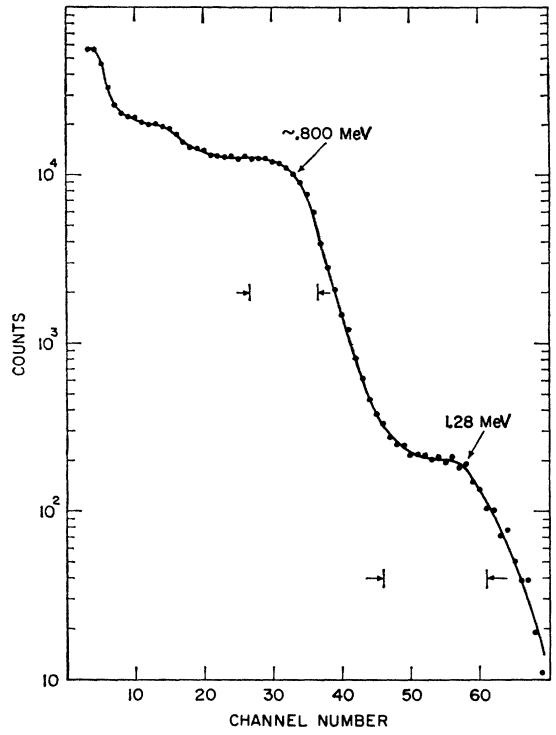

FIG. 16. Singles γ-ray spectrum of Tm^{168} and the two channels used in the determination of the 4+ state lifetime.

sponding to γ-ray energies between 550–800 keV. The half-life of this state was found to be (1.90±0.06) nsec. Figure 14 shows the time spectrum.

Figures 15 and 16 show the singles spectra in the electron and γ counters, respectively. The channels used for the 4+ state lifetime measurement are indicated on the figures. The K conversion line of the 198-keV γ ray falls just between the K and L lines of the 184-keV transition. It is evident that the one "clean" choice of a transition feeding the 4+ level is the 1.28-MeV γ ray. But the intensity of this transition is only ~4%, as compared to 10% for the 831-keV transition and 12% for the 633-keV transition. If one works with these more intense transitions, the channel cannot be set to exclude the 817-keV and 822-keV transitions, which are in coincidence with a number of transitions that would be detectable within the electron channel. Presumably, the lifetimes associated with these competing cascades and the lifetime of the 4+ states will show themselves on opposite slopes of the time spectrum. Arguments from level systematics suggest that these lifetimes would be extremely short. But to be certain that the *portion* of the slope from which we determine the 4+ state lifetime is not distorted by the presence of competing cascades, a comparison against the cleaner but less intense 1.28—0.184-MeV time spectrum was made as follows. Two energy selection channels were set on the γ spectrum. The time spectrum of coincidences with the 1.28-MeV γ ray was selectively stored in one-half of a split memory multichannel analyzer, and the spectrum of coincidences with the 600–800 keV group in the other half. Least-squares fits were made for equivalent portions of the respective spectra to ascertain the corresponding half-lives. The spectrum coincident with the 1.28-MeV transition gave a half-life of $(1.24\pm0.06)\times10^{-10}$ sec, the error here reflecting only statistics. The second spectrum gave 1.21×10^{-10} sec for the half-life, with a negligibly small statistical error.

Figure 17 shows a typical time spectrum obtained with the 600–800 keV group. The distribution is seen sitting on a "background", which are counts arising from coincidences through the 120-nsec state (see Appendix I). They appear on the side of negative delay time because some γ rays of the intense 448-keV transition are detected in the β counter. They appear on the side of positive delay as a result of the fairly high efficiency for summing in the γ counter. In determining the 4+ state lifetime these counts were treated as a flat background which extended into the region of the exponential slope. They were subtracted off before the above mentioned least-squares fits were made. Our assignment for the 4+ state half-life is $(1.21\pm0.08)\times10^{-10}$ sec.

VI. Hf^{180}

Reactor activation of natural hafnium yields activities of Hf^{180}, Hf^{181}, and Hf^{175} in order of decreasing relative abundance. The bombardments were made with an 0.008-in. cadmium absorber because we find that this enhances the high-spin Hf^{180m} activity relative to the Hf^{181} activity.

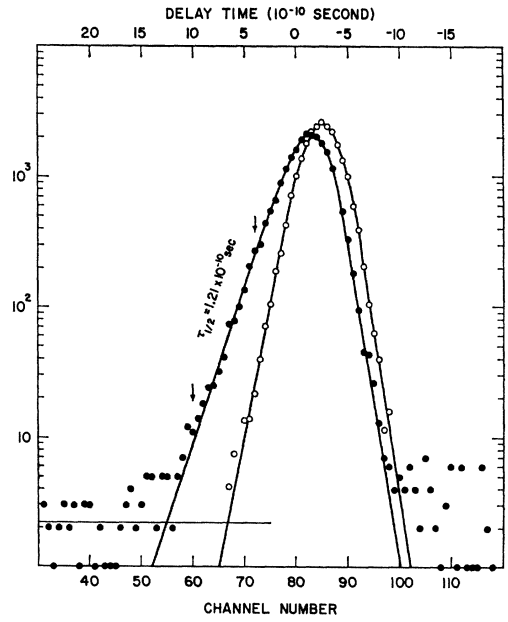

FIG. 17. Time spectrum of coincidences between the 184-keV transition and γ rays of 600–800 keV, giving the half-life of the 4+ state in Er^{168}.

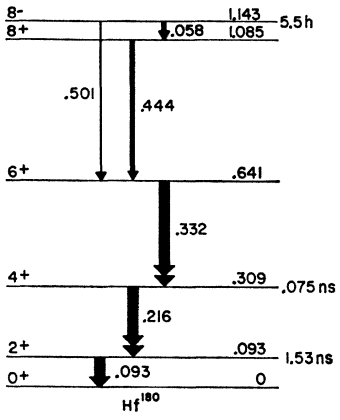

FIG. 18. Decay scheme of Hf^{180m} (see reference 11).

The decay scheme[11] of Hf^{180m} is seen in Fig. 18. The time distribution from delayed coincidence between the 93-keV L conversion line and any of the preceding γ rays, shown in Fig. 19, gives (1.53±0.05) nsec for the 2+ level half-life. The wing extending in the direction of negative time is due to the Hf^{181} contamination, in which a 133-keV γ ray is in coincidence with a 482-keV γ ray through a 10-nsec level. As the source aged, this wing remained while the rest of the spectrum disappeared with the Hf^{180m} half-life of 5.5 h.

The half-life of the 4+ state is too short to be clearly observable from the slopes of the time spectrum. An accurate determination of a lifetime from centroid shift measurements is often hindered by the difficulty of achieving complete stability against variation of system gain. Such instability can prevent a valid comparison between the spectrum of prompt events whose centroid defines time zero, and the spectrum of delayed events whose centroid should be displaced by the mean-life in question. A method described by Simms, Benczer-Koller, and Wu[12] can be very powerful in minimizing this problem. An adaptation of this method was employed for the Hf^{180} 4+ state measurement, with the electronic apparatus arranged as shown in Fig. 20.

A combination source of Hf^{180} and Na^{22} was viewed by a 5 in.×5 in. NaI(Tl) detector in addition to the two plastics. Energy channels were set to accept the 332-keV γ rays in one plastic and the 216-keV γ ray in the other. Both channels of course included the 511-keV annihilation quanta from Na^{22}, and coincidences between the plastic detectors yielded the time spectrum in the usual way. This spectrum would have been a mixture of the 511–511 keV coincidences and the 332–216 keV coincidence, but for the additional (triple) coincidence requirement with pulses in the NaI which sorted them out. If a 1.28-MeV pulse appeared in the NaI in coincidence with the two plastics, the event was identified with the Na^{22} decay and the time pulse was stored in one section of a split memory pulse-height analyzer. If a 444- or 501-keV γ ray appeared in the NaI, then Hf^{180} was identified, and the time pulse was routed to another section of the analyzer. The two annihilation quanta are of course in prompt coincidence. The sizes of the plastics were sufficiently small (1 in.×3/5 in. and 1 in.×3/4 in.) to make the difference in spatial distribution of interactions within them unimportant, as far as comparisons of 216 keV and 332 keV with 511 keV were concerned. The advantages of this way of simultaneously obtaining the prompt and delayed spectra are evident. Gain drifts in the system would tend to effect the two spectra in the same way. However, the following sources of error were still present and corrections had to be made for them:

(1) Misidentification of the Na^{22} coincidences as Hf^{180} coincidences. Figure 21 shows the singles pulse-height spectra obtained with a NaI(Tl) scintillator of Hf^{180} alone (A), and of Hf^{180} with Na^{22} (B). Small amounts of Hf^{181} and Hf^{175} were known to be present, but neither activity had triple cascades of the proper energy to interfere with the present experiment. The channels used are also shown on the figure. The Hf^{180} channel, of course, included some contributions from Compton distribution of the 1.28-MeV γ ray of Na^{22} detected in the NaI at the Hf peak channel position. To estimate the effect of this a run was made with Na^{22} alone. The number of counts appearing in the "wrong" section of the analyzer, i.e., the section which should have registered only Hf^{180} coincidences, was noted as a certain percentage of the true Na^{22} coincidences. The centroid shift

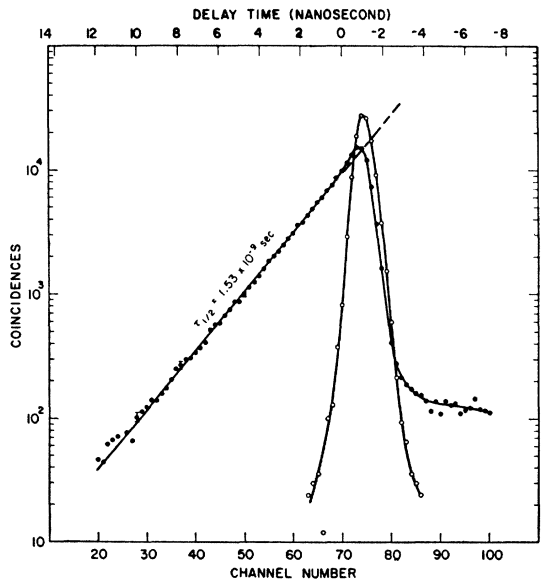

FIG. 19. Time spectrum of coincidences between the 93-keV transition and all preceding γ rays, giving the half-life of the 2+ state in Hf^{180}.

[11] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C.). The spin-parity of the isomeric state was changed to 8−, according to M. Deutsch and W. Bauer, Nucl. Phys. **21**, 128 (1960).

[12] P. C. Simms, N. Benczer-Koller, and C. S. Wu, Phys. Rev. **121**, 1169 (1961).

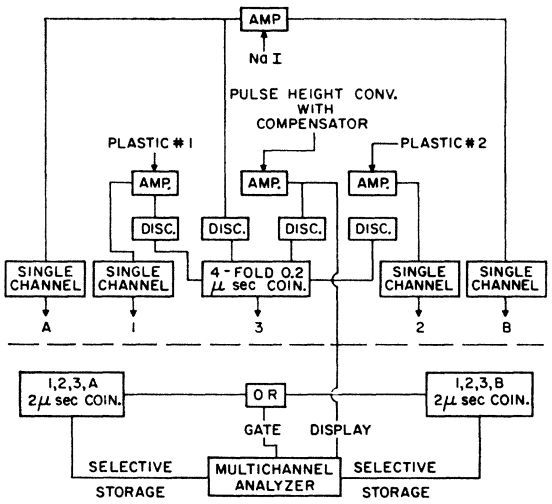

FIG. 20. Schematic diagram of the experimental arrangement for determination of the 4+ state lifetime in Hf^{180}.

between the distributions in the two sections was calculated, and for each run of the combined source, a correction of ~10% was made on the basis of the total Na^{22} coincidences for that run. The relative proportion of Na and Hf activities was slightly different for the individual runs in spite of our effort to duplicate the amounts as closely as possible. Table I shows the statistical distribution of the results of the runs. Comparison of internal and external errors shows this distribution to be very reasonable.

(2) Misidentification of the preceding and following radiations. In a centroid measurement, if the roles of the preceding and following radiations become inverted,

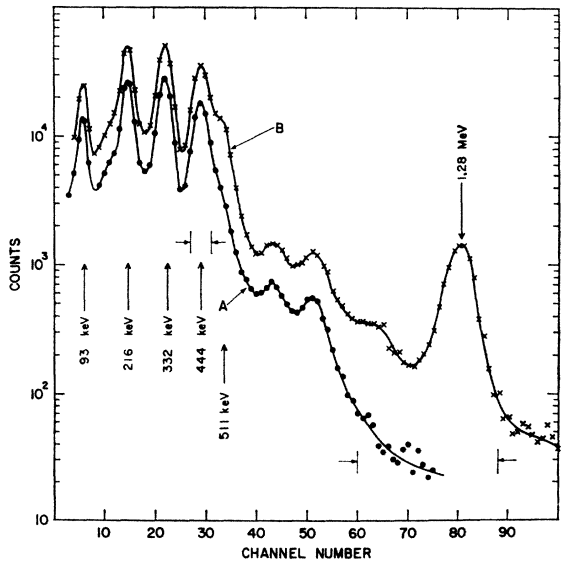

FIG. 21. (A.) Singles spectrum of a Hf^{180m} source, using a NaI detector. (B.) Singles spectrum of a mixed source of Hf^{180m} and Na^{22}. Channels shown are those used to sort out the two sets of coincidences.

TABLE I. Tabulation of the centroid shifts before and after correction for misidentified Na^{22} coincidences for each run in the measurement of the Hf^{180} 4+ state lifetime.

Run	Centroid[a] shift (psec)	Corrected[a] centroid shift (psec)
1	72±30	82±34
2	127±30	139±33
3	48±29	52±32
4	126±29	139±33
5	66±29	73±32
6	73±29	80±33
7	88±30	98±33
8	107±28	116±31
9	98±28	109±32
10	120±29	132±32
11	29±29	31±31
12	103±30	115±34
	Average	98±9.5[a]

[a] Note that this corresponds to mean life, *not* half-life of the state.

the result is a shift in the wrong sense of time. For this experiment, since the 216-keV channel necessarily included some 332-keV γ rays, it was important to exclude the 216-keV γ rays from the 332-keV channel. Curve A in Fig. 22 shows the γ-ray spectrum of Hf^{180} in the plastics, the rise at the end of the curve being due to amplifier saturation. Curve B shows the coincidence of the plastic spectrum with the 444–501 keV channel in the

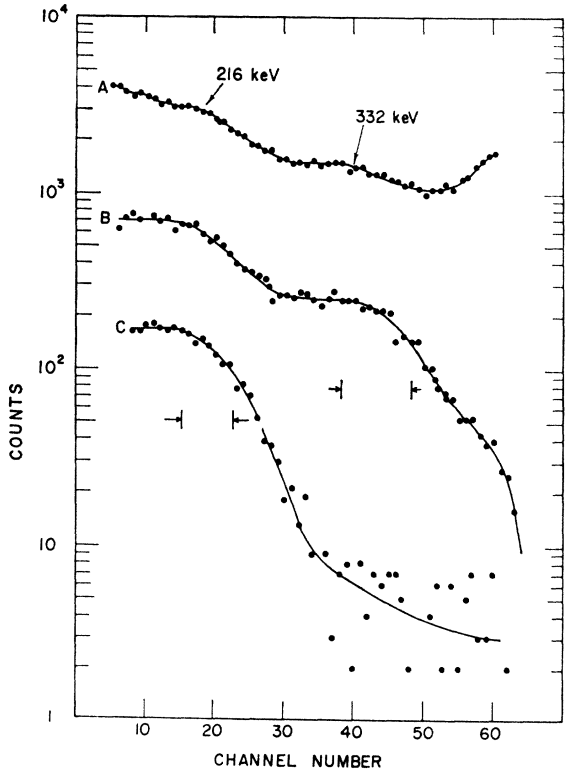

FIG. 22. (A.) Hf^{180} γ-ray spectrum in a plastic scintillator. (B.) Coincidence of *A* with the 444-501-keV channel in the NaI detector. (C.) Coincidence of *B* with the 332-keV channel in one plastic scintillator.

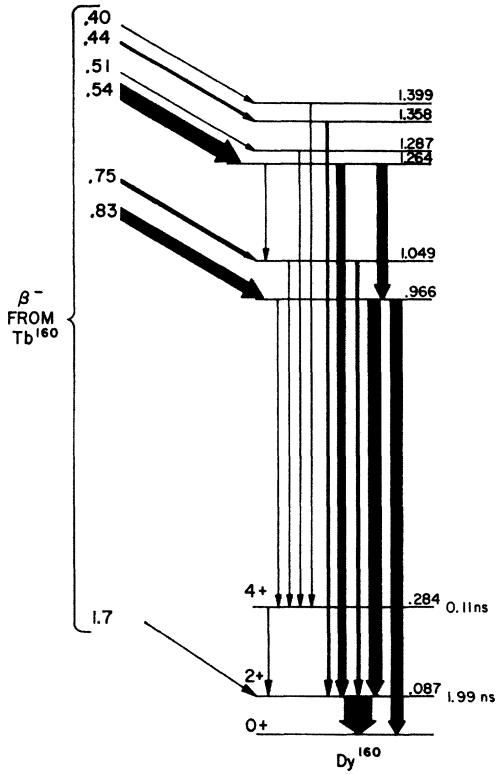

FIG. 23. Partial decay scheme of Tb^{160} (see reference 16).

NaI. Curve C is the plastic spectrum of triple coincidences with the 332-keV channel in one plastic and the 444–501 keV NaI channel. If the energy selection of the 444–501 keV and 332-keV channel were perfect, C would not have had any counts above the Compton edge of the 216-keV γ ray. Extrapolation from the region of spurious counts back to the region of the 216-keV channel gives the percentage of pulses in the time spectrum which must be corrected for having their centroid displaced in the wrong direction. The intensity of the misidentified coincidences was 3.5% of the total number. This resulted in a correction of 7 psec to the centroid separation.

(3) Accidental triple coincidences. This was a correction for accidental triple coincidences in which the two plastic double coincidence is true. Time pulses resulting from these tend to have their centroid in the same position as that of the unsorted double-coincidence time spectrum. We found accidentals of 4.6% in the Hf^{180} section and 2% in the Na^{22} of the analyzer.

In summary, our final result of $(7.5\pm1.0)\times10^{-11}$ sec for the Hf^{180} 4+ level half-life was obtained as follows: Average of the mean lives in column 3 of Table I gave a value of $\tau_m=98$ psec. Correction for accidentals changed τ_m to 101 psec. Further correction for misidentification of early and late radiations brought τ_m to 108 psec, which corresponds to a half-life of 7.5×10^{-11} sec.

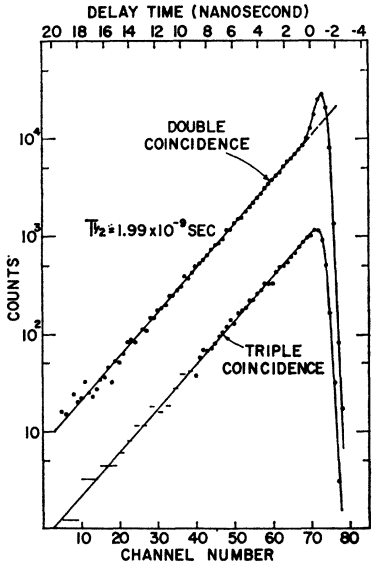

FIG. 24. Time spectra of coincidences between the 87-keV transition and preceding radiations in Dy^{160}. The line drawn through the point of the triple coincidence spectrum has the same slope as the line drawn for the double coincidence curve. Horizontal lines indicate the average of the number of counts in the respective channels.

VII. Dy^{160}

A separate introduction must be given to a discussion of the measurements on Dy^{160}. The decay scheme of $Tb^{160}\rightarrow Dy^{160}$ is very much more complicated than the other nuclei discussed here. Therefore, it is extremely difficult to obtain an accurate measurement of the 4+ lifetime using plastic scintillators for energy discrimination. The choice of this nucleus was dictated by the existing measurement of the 4+ lifetime by Burde and Rakavy.[13]

Burde and Rakavy measured the 4+ lifetime in Dy^{160} by the centroid-shift method using two magnetic spectrometers for energy resolution. They measured coincidences between the β continuum and the conversion line of the $4+\rightarrow 2+$ transition. The measurement was per-

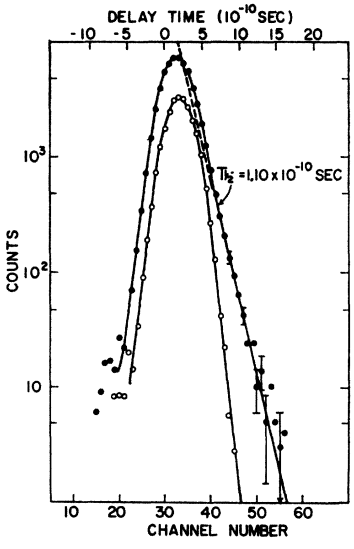

FIG. 25. Time spectrum of coincidences between the conversion line of the $4\rightarrow 2$ transition and the β continuum for Dy^{160}. (Circuit delays are arranged to show the lifetime on the high side of the time curve.[17] The prompt spectrum was obtained serving β-γ coincidences with Co^{60}.)

[13] J. Burde and M. Rakavy, Nucl. Phys. 28, 172 (1961).

formed by the self-comparison method, and a value of $\tau_{1/2}=(7.55\pm0.76)\times10^{-11}$ sec was determined. At the time only an older measurement of the 2+ lifetime was available with errors of about 20%. They compared the $B(E2;\ 4\rightarrow2)$ to the $B(E2;\ 2\rightarrow0)$ and obtained a value (1.65 ± 0.33) which agreed, within the large error, with the model prediction of 10/7.

Recently a precision measurement of the 2+ lifetime was reported by Fossan and Herskind.[14] They obtained the value $\tau_{1/2}(2+)=(1.92\pm0.05)\times10^{-9}$ sec. If this result is combined with the work of Burde and Rakavy, a ratio of $B(E2;\ 4\rightarrow2)/B(E2;\ 2\rightarrow0)=1.9\pm0.2$ is obtained. The error now is almost completely due to the quoted error of the measurement of Burde and Rakavy. This value is clearly in contradiction with the strong coupling model prediction of 1.43. It is the only known measurement on a nucleus in the rotational region which conflicts with the model prediction. For this reason we attempted to remeasure the 2+ and 4+ lifetimes in this case.

The equipment used was somewhat different from that used for the other nuclei. The 6BN6 circuit and 404A limiters were replaced by a transistorized time to pulse-height converter and a tunnel-diode fast discriminator for pulse shaping. A pulse-height compensator and block circuit were employed also. This system is described elsewhere.[15] The time calibrations were done by inserting fixed General Radio 50Ω lines into one of the timing signals. The calibration curves were linear over the ranges used to about 2% and are believed precise to this accuracy also.

A partial decay scheme of Tb^{160} which is produced by neutron capture by the monoisotopic natural Tb is shown in Fig. 23. The decay scheme is due to Ewan, Graham, and Geiger,[16] and only the more intense transitions are shown.

The 2+ lifetime was determined by observing the intense L conversion of the $2\rightarrow0$ transition in coincidence with γ rays whose Compton energy in the plastic scintillator is greater than about 500 keV. The time spectrum obtained is shown in Fig. 24. A prompt part observed is due mainly to coincidences between γ rays and electrons in the continuum β spectrum. In addition to this experiment, a triple coincidence measurement was made in which an auxiliary 1/4-in. thick β detector was placed directly behind the source between the source and γ detector. A triple coincidence was required in which an electron of energy greater than ~400 keV entered the third detector. The time spectrum in triple coincidence is shown in Fig. 24 and yields the same $\tau_{1/2}$ as the double-coincidence experiment. The prompt component is now absent as expected. The value for the 2+ lifetime which we obtain is $\tau_{1/2}=(1.99\pm0.05)\times10^{-9}$ sec, in excellent agreement with the results of Fossan and Herskind.

As can be seen from the decay scheme the 4+ level is fed only very weakly (~5%) in the Tb decay. In addition, the total conversion of the $4\rightarrow2$ transition is only 25%. The β spectra energies are also significantly higher than the $4\rightarrow2$ transition energy. In addition, transitions between the 1.264- and 1.049-MeV levels and between the 1.264- and 0.966-MeV levels result in conversion electrons of intensity comparable to the $4\rightarrow2$ transition. The Singles selectron spectrum obtained in the plastic scintillator shows essentially no line structure in the region of the K and L lines of the $4\rightarrow2$ transition. Thus special care must be taken in setting the energy channel in the conversion electron detector. Calibration of the detector energy scale was obtained using the conversion lines of Hf^{180}.

A γ-e coincidence time spectrum is almost completely dominated by prompt coincidences between γ rays and the continuum β spectrum. Preliminary experiments showed a small delayed tail on the time spectrum of γ-e coincidences with $\tau_{1/2}$ between 0.09 and 0.15 nsec depending on the position of the energy channel of the electron detector and upon the manner in which a visual resolution of the prompt and delayed components of the time spectrum was made.

A second experiment was performed by measuring electron-electron coincidences using two thin plastic scintillators. In this case, one channel was set at about 350 keV to detect β^- of the continuum. A time spectrum[17] obtained with the conversion electron detector window set in the region near the K conversion line of the 197-keV transition is shown in Fig. 25. A prompt component is still present and is due to coincidences between the β ray and conversion lines of transitions between the higher energy states which are unresolved from the $4\rightarrow2$ transition. Measurements were performed with different settings of the conversion electron detector channel (between about 100 keV and 250 keV). These spectra show varying ratios of prompt to delayed components, and for the lowest energy channel the $2\rightarrow0$ lifetime becomes evident as a long tail of low intensity. The highest energy channel used shows only a prompt distribution. Visual resolution of these time spectra show a lifetime between 0.10 and 0.12 nsec.

A third experiment utilizes a triple coincidence arrangement as described above for the 2+ lifetime measurement. Timing is measured between conversion electrons and γ rays above ~700 keV. A third counter records β rays of energy greater than ~250 keV. A typical time spectrum obtained in this way is shown in

[14] D. B. Fossan and B. Herskind, Phys. Rev. Letters **2**, 155 (1962).

[15] See reference 5 of this paper and *Nanosecond Counter Circuit Manual*, R. Sugarman, F. C. Merritt, and W. A. Higinbotham, Brookhaven National Laboratory Report BNL 711 (T-248), 1962.

[16] G. T. Ewan, R. L. Graham, and J. S. Geiger, Nucl. Phys. **22**, 610 (1961).

[17] In Figs. 25 and 26, time spectra are obtained with delays arranged so that the lifetime appears on the high side of the time spectrum. The detector for the preceding radiation was the one which was artificially delayed before time to amplitude conversion. This seemed to result in a slightly better prompt curve for reasons which we do not completely understand.

TABLE II. Half-lives of the 2+ and 4+ rotational states in the ground-state band in Dy^{160}, Dy^{162}, Er^{166}, Er^{168}, and Hf^{180}.

	Present work		Results of other experiments	
	$\tau_{1/2}(2+)$ (10^{-9} sec)	$\tau_{1/2}(4+)$ (10^{-10} sec)	$\tau_{1/2}(2+)$ (10^{-9} sec)	$\tau_{1/2}(4+)$ (10^{-10} sec)
Dy^{160}	1.99±0.05	1.07±0.15	1.92±0.05[a]	0.75±0.08[b]
Dy^{162}	2.25±0.07	1.32±0.08	2.22±0.14[c]	
Er^{166}	1.83±0.06	1.20±0.08	1.80±0.05[a]	
			1.81±0.17[c]	
			1.7 [d]	
Er^{168}	1.90±0.06	1.21±0.08	1.84±0.17[c]	
Hf^{180}	1.53±0.05	0.75±0.10	1.50±0.04[a]	
			1.65±0.10[e]	0.60±0.17[e]
			1.40±0.10[d]	

[a] Reference 14.
[b] Reference 13.
[c] M. Birk, G. Goldring, and Y. Wolfson, Phys. Rev. **116**, 730 (1959).
[d] A. W. Sunyar, Phys. Rev. **98**, 653 (1955).
[e] A. W. Sunyar, *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 14, p. 347.

Fig. 26. (The corresponding prompt time spectrum has a slope with $\tau_{1/2}\sim 0.05$ nsec.) The prompt component is now somewhat reduced since the high γ energy requirement precludes observation of some of the more intense competing conversion lines. However, even in this arrangement a variation in the observed $\tau_{1/2}$ was seen as the conversion electron channel position was varied between ~100 and 200 keV. This is again presumably due to the contribution of prompt coincidences with some weak transitions between the high-energy states. The variation in slope with energy was $\sim\pm 0.01$ nsec in the pertinent region.

It should be mentioned that possible lifetimes of the high excited states would appear in our time spectra on the opposite side of the time spectrum from that observed.

The 4+ state lifetime is taken to be an average of the two slightly different values obtained with double and triple coincidences when the electron channel was set at the 197-keV K line. In view of the various complications discussed, a large uncertainty is assigned to this measurement. The $\tau_{1/2}(4+)$ obtained is $(1.07\pm 0.15)\times 10^{-10}$ sec, the extremes of this value encompassing the whole range of the apparent variation of the time spectrum slope with electron energy selection. This value is clearly in disagreement with the centroid shift measurements of Burde and Rakavy. We have no explanation for this discrepancy.

RESULTS AND DISCUSSION

In Table II we have summarized the results of the above lifetime measurements. Included for comparison are values of these lifetimes already reported in the literature. It can be seen that there is very good agreement between our results and those of other workers.

The reduced transition probabilities given in Table III are calculated from our lifetimes.[18] The main contribution to the uncertainty in the ratio of $B(E2)$ is expected to result from the errors on the lifetime measurements. The calculation of $B(E2)$ involves the factors $(1+\alpha)$ and E^5, where α is the total internal conversion coefficient and E the energy of the transition. The values of α and E used are given in Table IV. We have taken E from the very accurate measurements of Harmatz *et al.*,[7] Jacob *et al.*,[10] Edwards and Boehm,[19] and Ewan *et al.*,[16] which have quoted errors of <0.15%. Therefore the uncertainty on the fifth power of the ratio of two energies is only about 1%. The internal conversion

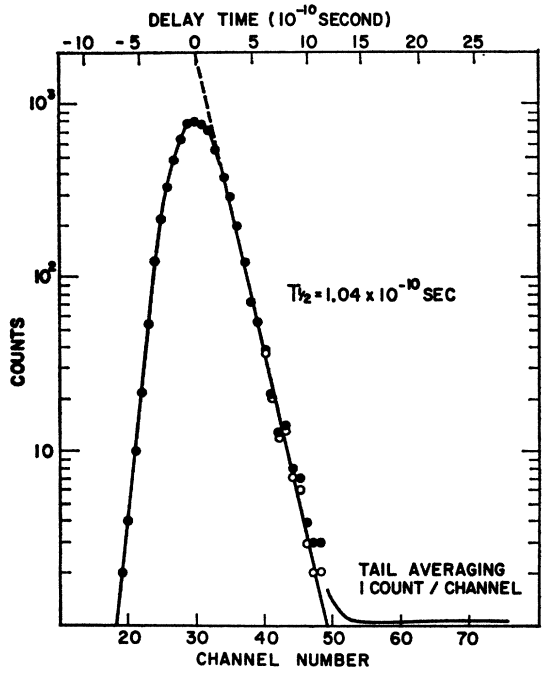

FIG. 26. Time spectrum of coincidences between conversion lines and γ rays above ~700 keV obtained in triple coincidence with a β ray in the decay $Tb^{160}\rightarrow Dy^{160}$.

TABLE III. Reduced E2 transition probabilities calculated from the present work, and the ratios $B(E2;4\rightarrow 2)/B(E2;2\rightarrow 0)$ of even-even rare-earth nuclei.

	$B(E2;4\rightarrow 2)$ ($e^2\times 10^{-48}$ cm^4)	$B(E2;2\rightarrow 0)$[a] ($e^2\times 10^{-48}$ cm^4)	$\frac{B(E2;4\rightarrow)2^b}{B(E2;2\rightarrow 0)}$
Dy^{160}	1.4	1.03	1.4
Dy^{162}	1.50	1.06	1.42
Er^{166}	1.69	1.19	1.42
Er^{168}	1.63	1.12	1.46
Hf^{180}	1.33	0.92	1.45
Gd^{156}	(Ofer)[c]		1.4 ±0.4

[a] $B(E2;2\rightarrow 0)$ is the radiative reduced transition probability, which differs from the $B(E2;0\rightarrow 2)$ obtained from Coulomb excitation by a factor of 5. In general

$$B(E2;I_1\rightarrow I_2)_{\text{rad}}=[(2I_2+1)/(2I_1+1)]B(E2;I_2\rightarrow I_1)_{\text{coul. ex.}}.$$

[b] Experimental errors on these numbers are discussed in the text. The apparent clustering of all the values at 1.43 suggests that any systematic error in our measurements is similar for all cases, or that we have been too conservative in estimating the possible errors. The actual statistical errors in these measurements are of the order of a few percent.
[c] Reference 21.

[18] $[B(E2)_{\text{radiative}}]^{-1}=1.23\times 10^{-2}E^5(1+\alpha)\tau_m$; E in keV, $B(E2)$ in units of $e^2\times 10^{-48}$ cm^4.

[19] W. F. Edwards and F. Boehm, Phys. Rev. **121**, 1499 (1961).

TABLE IV. Energies and total theoretical internal conversion coefficients of the $2+ \rightarrow 0+$ and $4+ \rightarrow 2+$ transitions within the ground-state band.

	Energy of transition (keV)			Theoretical internal conversion coefficient	
	$2+ \rightarrow 0+$	$4+ \rightarrow 2+$	$E(4+)/E(2+)$	$2+ \rightarrow 0+$	$4+ \rightarrow 2+$
Dy^{160}	86.7	197.0	3.27	4.60	0.25
Dy^{162}	80.7	185.2	3.30	5.96	0.31
Er^{166}	80.6	184.4	3.29	6.64	0.31
Er^{168}	79.8	184.5	3.31	7.21	0.34
Hf^{180}	93.3	215.3	3.31	4.70	0.23

coefficients were obtained by interpolating the theoretical values of α_K and α_L of Sliv and Band,[20] and taking the sum of the coefficients of the higher shells equal to $0.3\,\alpha_L$. We have not ascribed any error to the theoretical conversion coefficients obtained in this fashion since we have no basis for a quantitative estimate. The errors we assigned to the lifetimes have all been increased from statistical uncertainty to take account of possible systematic errors. The ratio $B(E2;\ 4\rightarrow 2)/B(E2;\ 2\rightarrow 0)$ should be accurate to 13% for Hf^{180}, 16% for Dy^{160}, and 7% for the other three as obtained from compounding the known assigned errors.

For transitions between states of a pure rotational band, the model predicts that $B(E2;4\rightarrow 2)/B(E2;\ 2\rightarrow 0)=10/7$. The values of this ratio are calculated from the present work, and these are given in Table III together with the values previously reported by Ofer[21] for Gd^{156}. Our values (and the Gd^{156} value) are clearly in very good agreement with the prediction.

The usual perturbations to the strong coupling model, namely, the rotation-vibration interaction and the rotation-particle interaction, are not expected to cause a serious change in $B(E2;\ 4\rightarrow 2)/B(E2;\ 2\rightarrow 0)$ from the value of 10/7. This expectation is based on considerations which attempt to relate the effect of the perturbations on the $B(E2)$ ratios to their effect on the energy E_I of the states of the ground-state band. The energies of the known states of these nuclei are well described by the expression $E_I=AI(I+1)-BI^2(I^2+1)$, with very small values of B/A ($\sim 10^{-3}$). We assume that the empirically determined value of B provides a measure of the magnitude of the perturbations. From this association we conclude that the deviation of the $B(E2)$ ratio from 10/7 is expected to be no more than a few percent. In order to study the above perturbations from these ratios, both the lifetimes and the internal conversion coefficients must be known to such high accuracy as to be experimentally not feasible at this time.

Recently some suggestions have been made that the $E2$ internal conversion coefficients are anomalous in this region.[22] Deviations from theoretical values of as much as 20% have been suggested. If such anomaly exists, then the $B(E2)$'s calculated using the theoretical coefficients would have to be modified accordingly. However, we note that there is excellent agreement between the model predicted 10/7 and the $B(E2;4\rightarrow 2)/B(E2;2\rightarrow 0)$ values calculated for each of the four nuclei. While we do not wish to argue that this constitutes a proof of the correctness of the theoretical internal conversion coefficients, it also seems unreasonable to dismiss it as an accident. To clear up the point, more work on the direct measurement of internal conversion coefficients should be undertaken, with an emphasis on reducing the experimental errors.

[20] L. Sliv and I. Band, Leningrad Physico-Technical Institute Report, 1956 [translation: Report 57 Icc K1, issued by Physics Department, University of Illinois, Urbana (unpublished)].
[21] S. Ofer, Phys. Rev. **115**, 412 (1959).
[22] E. M. Bernstein, Phys. Rev. Letters 8, 100 (1962).

ACKNOWLEDGMENTS

The authors are indebted to Dr. Joseph Weneser for his many pertinent comments on the theoretical aspects of this work. We also wish to thank Dr. Y. Y. Chu, Dr. G. T. Emery, and Dr. A. W. Sunyar for their aid to this work.

APPENDIX I

Additional Remarks on the Experimental Technique

Following are some comments pertinent to those lifetime measurements made from the slopes of the time spectra. Using β–γ coincidence rather than γ–γ coincidence was necessary for the 2+ state measurements because the Compton electron spectrum in the plastic scintillator due to 80-keV γ rays would be in the noise region of ordinary photomultipliers. For the case of the 4+ state, the $4+ \rightarrow 2+$ transition energies are all about 185 keV. The maximum of the corresponding Compton electron distribution would be at 80 keV, whereas the K and L conversion lines are around 130 and 175 keV. The factor of two difference in energy is an important consideration, in view of the rapid deterioration of resolution with decreased energy. We also observed that better prompt spectra were obtained with smaller sizes of scintillators. Electron detection, of course, lends itself more readily to the use of small scintillators. For these reasons the slope measurements were all performed by detection of conversion electrons.

At the energies which concern the present problem, the detection efficiency of the electron counter is close to unity, so that the over-all efficiency is essentially a function only of the geometry. Since the $2 \rightarrow 0$ transition is highly converted, a conversion electron from the $4 \rightarrow 2$ transition is nearly always followed by one of the $2 \rightarrow 0$ transition. Care must therefore be taken to position the source so as to have a small efficiency for summing. Failure to prevent summing can result in spurious effects in the time spectrum which reflect neither the 4+ nor the 2+ lifetime, but rather some unresolvable mixture of the two.

Working with a time-to-pulse height converter, the experimenter generally has a choice of making the slope characteristic of the decay appear on the side of the

time spectrum corresponding to bigger or to smaller pulses. It can be seen from the following considerations that there are advantages to choosing the side of smaller pulses. Consider a level populated by transition A and depopulated by transition B. Either A or B can be made "early" or "late" at the input to the time-to-pulse height converter. If A is "early," the characteristic slope appears on the side corresponding to smaller pulse; if "late," on the side of larger pulses. B is distributed in time relative to A according to $e^{-\lambda t}$. For the choice of "late" A, pulses of B farther out in time will be closer to maximum overlap with A. In fact, a point will be reached when B pulses very far out in time will have passed beyond maximum overlap. Thus the height of the pulses at the output of the time-to-pulse height converter increase with time to a maximum, then decrease again, so that the time spectrum folds back on itself. For the alternative choice of "early" A, this cannot happen because B pulses far out in time will simply overlap less and less with A until no coincidence output results at all.

APPENDIX II

Lifetime of 4+ State in Ni^{60}

For the purposes of centroid shift measurements of lifetimes, it is necessary to have a comparison source to define the zero of time which has a cascade through a very short-lived state. A convenient source which has been used for many measurements is Co^{60} whose decay scheme is shown in Fig. 27. The lifetime of the 2+ state has been measured by resonance fluorescence. However, the lifetime of the 2.50-MeV 4+ state has never been directly measured. This lifetime has been inferred from theoretical considerations. According to the vibrational model of Scharff-Goldhaber and Weneser,[23] the $B(E2; 4 \rightarrow 2)/B(E2; 2 \rightarrow 0) = 2$. Thus the lifetime expected for the 4+ state is $\tau_{1/2} = 1.4 \times 10^{-12}$ sec.

The 4+ state of Ni^{60} has been excited in high energy electron scattering experiments by a direct $E4$ transition by Crannell *et al.*[25] Measurements of a very weak branch from the 4+ state to the Ni^{60} ground state, in the decay of Co^{60}, has been reported by Morinaga and Takahashi.[24] By combining these two measurements a lifetime of $\tau_m = 3 \times 10^{-11}$ sec was inferred[25] for the 4+ lifetime. This is in serious disagreement with the model prediction.

In order to clarify this situation, and also to determine that Co^{60} used for β–γ coincidence measurements is a prompt source, we have attempted to measure the lifetime of the state.

One of the difficulties in this measurement is to find a prompt source for comparison. Such a source must contain a β decay of energy greater than $\sim$250 keV followed by a γ ray of reasonably high energy. The decay scheme must be well known, competing cascades must be weak, and the lifetime of the excited state short and well known. Since it was desired to perform a simultaneous two-source centroid shift measurement as for the Hf^{180} experiment described above, it is also necessary that the prompt source contain a third, coincident radiation for the triple coincidence requirement.

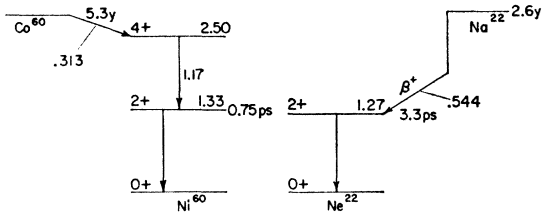

FIG. 27. Decay schemes of Na^{22} and Co^{60}. Half-lives of 2+ states taken from reference 11.

The conditions set forth above are met by the decay of Na^{22} to Ne^{22} illustrated in Fig. 27.

The experiment was performed with a mixed source of Na^{22} and Co^{60}. One of the fast scintillators detected a β^- from Co^{60} or a β^+ from Na^{22}. Energy selection was made near the upper end of the Co^{60} β spectrum. The second fast scintillator channel which accepted Compton events from the 1.13- or 1.17-MeV γ rays of Ni^{60} or the 1.28-MeV γ ray of Ne^{22} was set near the upper edge of this composite Compton distribution.

Two NaI(Tl) detectors (5 in.$\times$5 in. and 3 in.$\times$3 in.) viewed the source at 180° to one another and at 90° to the two fast detectors. The time signal derived from the fast detectors was displayed on the multichannel analyzer in either of two halves. The criterion for routing the time pulse was as follows. For a Co^{60} event a triple coincidence was required between the two fast detectors and a pulse in either of the 1.17–1.33 MeV photopeaks in the 5 in.$\times$5 in. detector. For the Na^{22} event a fourfold coincidence was required between the two fast detectors, a pulse greater than $\sim$300 keV in the 5 in.$\times$5 in. detector and a pulse in the annihilation radiation photopeak in the 3 in.$\times$3 in. NaI detector. The detection of both annihilation quanta in the NaI detectors was required to attempt to ensure that this radiation, which is in general delayed with respect to the β^+ and 1.28-MeV γ ray would not be detected in either of the timing counters.

Preliminary experiments indicated that some spurious events might be recorded and these were ascribed mainly to the following causes.

(1) The back-scattered Compton γ ray from the plastic γ detector could re-enter the β detector and simulate an electron pulse which is late.

(2) The annihilation radiation from positrons in the β detector might leave a small energy in the β detector due to a Compton scattering, and this energy is deposited "late" due to the β^+ lifetime.

[23] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).
[24] H. Morinaga, and K. Takahashi, J. Phys. Soc. Japan **14**, 1460 (1959).
[25] H. Crannell, R. Helm, H. Kendall, J. Oeser, and M. Yearian, Phys. Rev. **123**, 923 (1961).

TABLE V. Tabulation of centroid shifts observed in the measurement of the lifetime of the 4+ state of Ni^{60}. Negative signs indicate that the Na^{22} centroid appeared late.

Run number	Centroid shift Delay of Co^{60} distribution in picoseconds
1	-7.6 ± 6.2
2	-3.5 ± 2.8
3	-7.3 ± 3.8
4	$+2.8\pm3.5$
5	-3.1 ± 4.1
Weighted average	-3.0 ± 1.7

(3) Back scattering of β^- or β^+ from surrounding surfaces could result in a "late" β pulse due to the increased flight path of the electron.

In order to decrease these effects, a very small detector was used for the electrons and the activity was deposited within it. The β detector was 3 mm$\times$3 mm $\times$1 mm thick with a small hole drilled into its center. High specific activity Co^{60} and Na^{22} were deposited in this hole. Thus the γ detection efficiency (for seeing the β^+ annihilation radiation in particular) was very small in this detector. In addition, careful shielding and absorbers between the crystals were used. Also, many tests were performed with separate sources as well as with the mixed source recording the double, triple, and fourfold coincidence time spectra.

From the decay schemes of Fig. 27 and the experimental arrangement, one derives that the observed centroid shift Δ of the time distributions should be given by the following expression:

$$\Delta=\tfrac{1}{2}\tau_m(Ni^{60}4+)+\tfrac{1}{2}[\tau_m(Ni^{60}4+)+\tau_m(Ni^{60}2+)]-\tau_m(Ne^{22}2+). \quad (1)$$

The first two terms are derived assuming that the detection efficiency for the 1.17- and 1.33-MeV γ rays from Co^{60} are equal in both the NaI detector and the plastic detector. Using the values for $\tau_{1/2}(Ni^{60}2+)$ and $\tau_{1/2}(Ne^{22}2+)$ given in the decay schemes of Fig. 27, Eq. (1) yields

$$\tau_m(Ni^{60}4+)=(\Delta+3.9)\text{psec}. \quad (2)$$

Table V lists the observed centroid shifts for five separate runs totaling approximately 35 000 coincidences for each of the time distributions. The quoted errors are purely statistical. Some variations of channel position, geometric condition, fixed inserted delay, and interchange of routing signals were made for the different runs. Within the statistics no effect was observed due to these changes. Table V gives the average value of $\Delta=-(3.0\pm1.7)$ psec. The internal and external errors of this data are essentially equal.

Inserting this value into Eq. (2) yields $\tau_m(Ni^{60}4+)=(0.9\pm1.7)\times10^{-12}$ sec. This error quoted is purely statistical. From our experience with larger β scintillators and the attendant difficulties enumerated above, we would allow for a systematic error of the order of 5 psec and consider this experiment to yield an upper limit of $\tau_m<5\times10^{-12}$ sec for the mean life of the 4+ state of Co^{60}.

This result is in disagreement with the result inferred by Crannell *et al.* from their work and that of Morinaga and Takahashi. It is in agreement with a recent determination by a method similar to ours by Lee and Wu.[26] They also obtained a limit of $\tau_m<5\times10^{-12}$ sec. This result is also in agreement with the prediction of the vibrational model.

[26] Y. K. Lee and C. S. Wu, Bull. Am. Phys. Soc. **7**, 341 (1962).