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Rules for Spin and Parity Assignments Based on Log*ft* Values*

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A survey was made of log*ft* values for forbidden β transitions. Three cases, ^{90m}Y, ^{65}Ni, and ^{144}Pm decays, were examined experimentally. A number of low log*ft* values reported in the literature are superseded by more recent larger values. Empirical rules for making spin and parity assignments from log*ft* values are proposed.

I. INTRODUCTION

Since the comparative β-decay half-life or *ft* value was first introduced,[1] spin and parity assignments for nuclear energy levels have been made on the basis of log*ft* values. Of the $\approx$6500 definite or tentative J^π assignments that now exist in the *Nuclear Data Sheets*,[2] $\approx$1000 depend at least partly on log*ft* values. The existing rules[3] have evolved from previous compilations of log*ft* values.[4-6] The justification for such rules tends to be slightly circular since the β classifications (allowed, first-forbidden, etc.) employed in support of a rule may, in fact, have been assigned employing that rule or a similar rule. In 1963, Gleit, Tang, and Coryell[4] found only 46 cases where the forbiddenness category[7] could be obtained without any resort to log*ft* values. The situation has since improved.

In the present study, we have evaluated and compiled into five tables and one histogram β transi-

TABLE I. First-forbidden nonunique ($\Delta J=0$ or 1, parity change) β transitions (we consider only those cases in which the spin and parity assignments are definite) with log$ft \leq 6.0$.

Initial → Final nucleus nucleus	Type of decay	$J^{\pi}_{i} \rightarrow J^{\pi}_{f}$	Logft [a]	Reference
${}^{207}_{81}\mathrm{Tl}_{126} \rightarrow {}^{207}_{82}\mathrm{Pb}_{125}$	β^-	$\frac{1}{2}^+ \rightarrow \frac{1}{2}^-$	5.1	b
${}^{210}_{82}\mathrm{Pb}_{128} \rightarrow {}^{210}_{83}\mathrm{Bi}_{127}$	β^-	$0^+ \rightarrow 0^-$	5.1	c
${}^{206}_{81}\mathrm{Tl}_{125} \rightarrow {}^{206}_{82}\mathrm{Pb}_{124}$	β^-	$0^- \rightarrow 0^+$	5.2	d
${}^{206}_{80}\mathrm{Hg}_{126} \rightarrow {}^{206}_{81}\mathrm{Tl}_{125}$	β^-	$0^+ \rightarrow 1^-$	5.2	d
		$0^+ \rightarrow 0^-$	5.4	d
${}^{209}_{82}\mathrm{Pb}_{127} \rightarrow {}^{209}_{83}\mathrm{Bi}_{126}$	β^-	$\frac{9}{2}^+ \rightarrow \frac{9}{2}^-$	5.5	e
${}^{241}_{94}\mathrm{Pu}_{147} \rightarrow {}^{241}_{95}\mathrm{Am}_{146}$	β^-	$\frac{5}{2}^+ \rightarrow \frac{5}{2}^-$	5.8	f
${}^{199}_{79}\mathrm{Au}_{120} \rightarrow {}^{199}_{80}\mathrm{Hg}_{119}$	β^-	$\frac{3}{2}^+ \rightarrow \frac{5}{2}^-$	5.9	g
${}^{166}_{66}\mathrm{Dy}_{100} \rightarrow {}^{166}_{67}\mathrm{Ho}_{99}$	β^-	$0^+ \rightarrow 1^-$	5.9	h
${}^{15}_{6}\mathrm{C}_{9} \rightarrow {}^{15}_{7}\mathrm{N}_{8}$	β^-	$\frac{1}{2}^+ \rightarrow \frac{1}{2}^-$	6.0	i
${}^{113m}_{49}\mathrm{In}_{64} \rightarrow {}^{113}_{48}\mathrm{Cd}_{65}$	ϵ	$\frac{1}{2}^- \rightarrow \frac{1}{2}^+$	5.1	j
			>6.5	k

[a] Calculated from the experimental information contained in the references cited. The Q values were obtained from A. H. Wapstra and N. B. Gove, Nucl. Data A9, 265 (1971).

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tions from eight forbiddenness categories (a total of 160 logft values). The present collection is not complete; for allowed and first-forbidden nonunique transitions, only selected cases are discussed here. Also, many transitions whose forbiddenness classification depends crucially on logft arguments are not included.

We have systematically surveyed and extracted data from publications prior to April 1971 and have also included some data from more recent publications. The logft values listed in this paper are generally accurate to ±0.1; rarely do the uncertainties exceed 0.2. The exact uncertainties are relatively unimportant for our purposes except for those logft values that serve to define a J^{π} assignment rule.

The availability of high-resolution Ge(Li) detectors has resulted in a proliferation of logft values. The good accuracy presently attainable in the determination of γ intensities has led not only to the postulation of many β branches, often extremely weak, deduced from γ-intensity imbalances at levels, but also to more reliable logft values. In the study of nuclei far from the stability line, logft values often provide the only clue as to the nature of the states in question. For these reasons, a reexamination of J^{π} assignment rules based on logft values is appropriate at this time.

II. LOG*ft* CALCULATIONS

The logft values were computed with the computer program described by Gove and Martin.[8] The definition for f follows closely the work of Konopinski.[1,9] The t in ft is the partial half-life in seconds of the decay branch under study. Reviews of β-decay theory have been given by several authors including Schopper,[10] and Wu and Moszkowski.[11] The expression for f, as given by Gove and Martin[8] involves choices of nuclear radius, screening corrections, and finite nuclear size corrections. The radius formula is taken from Elton.[12] The screening corrections have been carried out by the WKB method of Rose[13] with screening energies from Garrett and Bhalla,[14] adjusted in the case of low-energy positrons to match the results of Behrens and Janecke.[15] The finite nuclear size correction is that of Rose and Holmes.[16]

For the case of electron capture (or positron

TABLE II. Logft values for $0^+ \rightarrow 0^+$, isospin forbidden β transitions (based on original literature surveyed before April 1971).

Initial → Final nucleus nucleus	Type of decay	$J^{\pi}_i \rightarrow J^{\pi}_f$	Logft [a]	Reference
^{64}Ga → ^{64}Zn	β^+, ϵ	$0^{(+)} \rightarrow 0^+$	6.5	b
^{66}Ge → ^{66}Ga	β^+, ϵ	$0^+ \rightarrow 0^{(+)}$	>7.4	c
^{66}Ga → ^{66}Zn	β^+, ϵ	$0^{(+)} \rightarrow 0^+$	7.9	d
^{156}Eu → ^{156}Gd	β^-	$0^+ \rightarrow 0_1^+$	9.8	e
		$0^+ \rightarrow 0_2^+$	10.2	f
		$0^+ \rightarrow 0_3^+$	9.6	g
^{170}Lu → ^{170}Yb	β^+, ϵ	$0^+ \rightarrow 0^+$	9.8	h
^{188}W → ^{188}Re	β^-	$0^+ \rightarrow (0^+)$	9.9	i
^{234}Np → ^{234}U	β^+, ϵ	$(0^+) \rightarrow 0_1^+$	8.5	j
		$(0^+) \rightarrow 0_2^+$	9.2	j
		$(0^+) \rightarrow 0_3^+$	9.0	j

[a] Calculated from the experimental information contained in the references cited. The Q values were obtained from A. H. Wapstra and N. B. Gove, Nucl. Data A9, 265 (1971).

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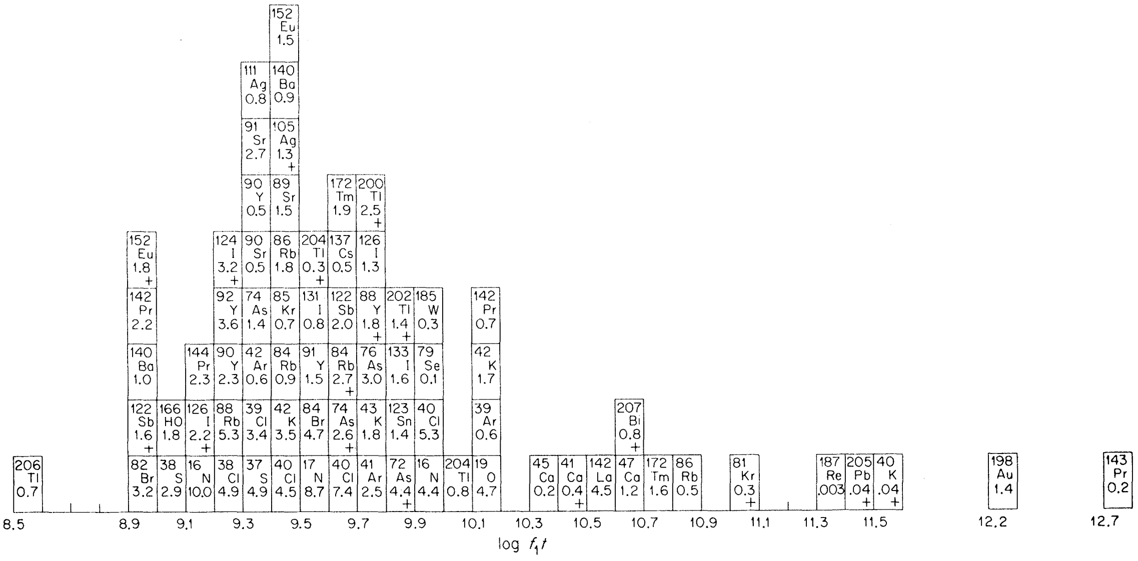

FIG. 1. Logf_1t values for unique first-forbidden β transitions identified by isotope and decay energy in MeV. A positive sign at the lower right-hand corner identifies ϵ or $(\epsilon + \beta^+)$ decay.

TABLE III. Log*ft* values for second-forbidden nonunique ($\Delta J = 2$, no parity change) β transitions [based on original literature surveyed before February 1971, and *Nuclear Data Sheets* (see Ref. d) published before January 1972].

Initial → Final nucleus nucleus	Type of decay	$J^{\pi}_{i} \rightarrow J^{\pi}_{f}$	Log*ft* [a]	Reference
(i) $T_{1/2} > 25$ yr; I_{β} or $I_{\epsilon} > 1.8\%$				
$^{36}Cl \rightarrow {}^{36}S$	ϵ	$2^{+} \rightarrow 0^{+}$	13.5	b
$^{129}I \rightarrow {}^{129}Xe$	β^{-}	$\frac{7}{2}^{+} \rightarrow \frac{3}{2}^{+}$	13.5	c
$^{36}Cl \rightarrow {}^{36}Ar$	β^{-}	$2^{+} \rightarrow 0^{+}$	13.3	b
$^{97}Tc \rightarrow {}^{97}Mo$	ϵ	$(\frac{9}{2}^{+}) \rightarrow \frac{5}{2}^{+}$	13.1	d
$^{135}Cs \rightarrow {}^{135}Ba$	β^{-}	$\frac{7}{2}^{+} \rightarrow \frac{3}{2}^{+}$	13.1	c
$^{53}Mn \rightarrow {}^{53}Cr$	ϵ	$\frac{7}{2}^{-} \rightarrow \frac{3}{2}^{-}$	12.6	d
$^{99}Tc \rightarrow {}^{99}Ru$	β^{-}	$\frac{9}{2}^{+} \rightarrow \frac{5}{2}^{+}$	12.3	c
$^{137}Cs \rightarrow {}^{137}Ba$	β^{-}	$\frac{7}{2}^{+} \rightarrow \frac{3}{2}^{+}$	12.1	b
$^{94}Nb \rightarrow {}^{94}Mo$	β^{-}	$6^{+} \rightarrow 4^{+}$	12.0	c
$^{59}Ni \rightarrow {}^{59}Co$	ϵ	$\frac{3}{2}^{-} \rightarrow \frac{7}{2}^{-}$	11.9	d
(ii) 15 h $< T_{1/2} <$ 3 yr; $I_{\beta} < 0.4\%$ Direct observation of weak, high-energy β groups				
$^{134}Cs \rightarrow {}^{134}Ba$	β^{-}	$4^{+} \rightarrow 2_{1}^{+}$	14.1	e
$^{58}Co \rightarrow {}^{58}Fe$	β^{+}, ϵ	$2^{(+)} \rightarrow 0^{+}$	12.9	d
$^{46}Sc \rightarrow {}^{46}Ti$	β^{-}	$4^{+} \rightarrow 2^{+}$	12.9	d
$^{24}Na \rightarrow {}^{24}Mg$	β^{-}	$4^{+} \rightarrow 2_{1}^{+}$	12.7	f
$^{134}Cs \rightarrow {}^{134}Ba$	β^{-}	$4^{+} \rightarrow 2_{2}^{+}$	12.5	e
$^{59}Fe \rightarrow {}^{59}Co$	β^{-}	$\frac{3}{2}^{-} \rightarrow \frac{7}{2}^{-}$	11.0	g
$^{95}Zr \rightarrow {}^{95}Nb$	β^{-}	$(\frac{5}{2})^{+} \rightarrow (\frac{9}{2})^{+}$	10.6	h
$^{95}Nb \rightarrow {}^{95}Mo$	β^{-}	$(\frac{9}{2})^{+} \rightarrow \frac{5}{2}^{+}$	9.7 $\geq$10.8	i j
(iii) Low-energy β or ϵ capture branch inferred from γ-ray measurements				
$^{208}Po \rightarrow {}^{208}Bi$	ϵ, α	$0^{+} \rightarrow (2)^{+}$	13.6	d
$^{207}Bi \rightarrow {}^{207}Pb$	$\beta^{+}, \epsilon, \alpha$	$\frac{9}{2}^{-} \rightarrow \frac{5}{2}^{-}$	12.2	d
$^{89}Sr \rightarrow {}^{89}Y$	β^{-}	$\frac{5}{2}^{+} \rightarrow \frac{9}{2}^{+}$	12.0	k
$^{152}Eu \rightarrow {}^{152}Sm$	ϵ	$3^{-} \rightarrow (5^{-})$	>11.4	l
$^{152}Eu \rightarrow {}^{152}Gd$	β^{-}	$3^{-} \rightarrow (5^{-})$	>11.3	l
$^{205}Bi \rightarrow {}^{205}Pb$	β^{+}, ϵ	$\frac{9}{2}^{-} \rightarrow \frac{5}{2}^{-}$	10.9	m, d
$^{24}Na \rightarrow {}^{24}Mg$	β^{-}	$4^{+} \rightarrow 2_{2}^{+}$	10.7 10.0 >11.2	n o p
$^{144}Pm \rightarrow {}^{144}Nd$	ϵ	$(5^{-}, 6^{-}) \rightarrow (3^{-})$	10.6 >10.9 >11.1	q r s
$^{153}Sm \rightarrow {}^{153}Eu$	β^{-}	$(\frac{3}{2}^{-})^{t} \rightarrow \frac{7}{2}^{-}$	10.0	t
$^{194}Au \rightarrow {}^{194}Pt$	β^{+}, ϵ	$1^{(-)} \rightarrow (3)^{-}$	9.6	u
$^{204}Bi \rightarrow {}^{204}Pb$	β^{+}, ϵ	$6^{(+)} \rightarrow 4_{2}^{+}$	>9.0	d
$^{65}Ni \rightarrow {}^{65}Cu$	β^{-}	$\frac{5}{2}^{-} \rightarrow \frac{1}{2}^{-}$	>8.8 >10.3	v s

TABLE III *(Continued)*

Initial → Final nucleus	Type of decay	$J^{\pi}{}_{i} \to J^{\pi}{}_{f}$	Log*ft* [a]	Reference
$^{47}Ca \to {}^{47}Sc$	β^-	$(\frac{7}{2})^- \to \frac{3}{2}^-$	>8.8 >9.0	w x
$^{151}Gd \to {}^{151}Eu$	ϵ	$\frac{7}{2}^- \to \frac{11}{2}^-$	>7.7	y
$^{63}Zn \to {}^{63}Cu$	β^+, ϵ	$\frac{3}{2}^- \to \frac{7}{2}^-$	7.2	z

[a] Calculated from the experimental information contained in the references cited. The Q values were obtained from A. H. Wapstra and N. B. Gove, Nucl. Data A9, 265 (1971).

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decay + electron capture) the definition of f is that given by Gove and Martin.[8] In that work, the wave functions were computed with the Oak Ridge National Laboratory Atomic Wave Function Code.[17] The exchange and overlap correction factors were computed in the manner of Bahcall.[18]

For first-forbidden unique and second-forbidden unique transitions, we computed $\log f_1 t$ and $\log f_2 t$ values, respectively, as defined by Gove and Martin[8] on the basis of expressions given by Konopinski[9] and by Warburton, Harris, and Alburger.[19] Tables of $\log_{10}(f_1/f)$ are given by Gove and Martin.[8] The present definition of $\log_{10} f_1$ gives values that are larger by $\log_{10} 12 = 1.08$ than those in many earlier works, e.g. Davidson.[20]

III. FORBIDDENNESS CATEGORIES

A. First-Forbidden Nonunique Transitions

Cases where $\log ft \leq 6.0$ are shown in Table I. Also shown in Table I is the case of ^{113m}In decay for which a reported $\log ft = 5.1$ was refuted by later work. Of the 10 cases with $\log ft \leq 6.0$, the six lowest ones are for nuclei close to the $Z = 82$, $N = 126$ closed shells. Therefore, we propose the following rules: *For Z (daughter nucleus)* <80, *β transitions with logft<5.9 are allowed. For Z ≥80, β transitions with logft<5.1 are allowed.*

We stress here that the converse of the above rule (statements such as "transitions with $\log ft \geq 5.9$ are not allowed") or of the other rules proposed herein is demonstrably false. We cite two extreme examples. The allowed β^- decay from the ^{152}Eu, 3^- ground state to the 1124-keV 3^- level in ^{152}Gd has a log*ft* value[21] of 10.6. The first-forbidden β^- decay from the ^{176}Lu 7^- ground state to the 596-keV 6^+ level has a log*ft* value[22] of 18.7. The large hindrance in the case of ^{176}Lu decay is understood in terms of *K* forbiddenness.[11]

B. $0^+ \rightarrow 0^+$ Isospin Forbidden Transitions

The $0^+ \rightarrow 0^+$ β transition between two members of an isospin multiplet (i.e., between analog states) is a superallowed β transition with a log*ft* value in the 3.48–3.50 range.[11, 23] When there is a change of isospin between the initial and final states, the $0^+ \rightarrow 0^+$ β transition is strongly hindered, as was pointed out by Alford and French.[24] In fact, the log*ft* value in such cases is a measure of the magnitude of isospin mixing.[25]

In Table II, we have presented all known cases of this type. The lowest reported log*ft* value is 6.5 in the case of ^{64}Ga decay.[26] The isospin selection rules therefore imply that *logft values in the 3.6–6.4 range are inaccessible to* $0^+ \rightarrow 0^+$ *decays.*

C. First-Forbidden Unique Transitions

The present compilation of 77 cases is shown in Fig. 1 as a histogram. Only those cases where the J^π assignments, β energies, and β intensities are all fairly definite are included.[27, 28]

In the experimental part of this paper, we show that the reported low $\log f_1 t$ value of 7.3 in ^{90m}Y decay is incorrect. The next lowest value of 8.5 occurs in ^{206}Tl decay investigated by Zoller and Walters.[29] A confirmation of this value would be desirable.

The $\log f_1 t$ values range from 8.5 to 12.7 with an average value of 9.7. More than 80% of the cases lie in the narrow range 8.9–10.2. The proposed rule is: *First-forbidden unique* β *transitions have* $\log f_1 t \geq 8.5$.

TABLE IV. Log*ft* values for second-forbidden unique ($\Delta J = 3$, no parity change) β transitions (based on original literature surveyed before April 1971).

Initial nucleus → Final nucleus	Type of decay	$J^\pi_i \rightarrow J^\pi_f$	Log*ft* [a]	$\mathrm{Log} f_2 t$ [b]	Reference
$^{22}\mathrm{Na} \rightarrow {}^{22}\mathrm{Ne}$	β^+, ϵ	$3^+ \rightarrow 0^+$	12.8	14.9	c
$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni}$	β^-	$5^+ \rightarrow 2_1^+$	12.9	14.6	d
$^{26}\mathrm{Al} \rightarrow {}^{26}\mathrm{Mg}$	ϵ	$5^+ \rightarrow 2_2^+$	13.3	14.6	e
$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni}$	β^-	$5^+ \rightarrow 2_2^+$	13.3	13.9	f
$^{10}\mathrm{Be} \rightarrow {}^{10}\mathrm{B}$	β^-	$0^+ \rightarrow 3^+$	13.4	13.8	g
$^{209}\mathrm{Po} \rightarrow {}^{209}\mathrm{Bi}$	ϵ	$\frac{1}{2}^- \rightarrow \frac{7}{2}^-$	13.6	14.6	h
$^{26}\mathrm{Al} \rightarrow {}^{26}\mathrm{Mg}$	β^+, ϵ	$5^+ \rightarrow 2_1^+$	14.2	15.7	e
$^{208}\mathrm{Po} \rightarrow {}^{208}\mathrm{Bi}$	ϵ	$0^+ \rightarrow (3)^+$	14.8	15.4	i
$^{123}\mathrm{Te} \rightarrow {}^{123}\mathrm{Sb}$	ϵ	$\frac{1}{2}^+ \rightarrow \frac{7}{2}^+$	≈18	≈15.6	j
$^{138}\mathrm{La} \rightarrow {}^{138}\mathrm{Ba}$	ϵ	$5^+ \rightarrow 2^+$	≈18	≈18	k
$^{138}\mathrm{La} \rightarrow {}^{138}\mathrm{Ce}$	β^-	$5^+ \rightarrow 2^+$	≈18	≈18	k

[a] Log*ft* value calculated as if the β transition is allowed. The relevant experimental information for calculating the log*ft* values is contained in the references cited. The *Q* values were obtained from A. H. Wapstra and N. B. Gove, Nucl. Data A9, 265 (1971).

[b] Log*ft* value with second-forbidden corrections (see text for details).

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D. Second-Forbidden Nonunique Transitions

A critical evaluation of second-forbidden nonunique log*ft* values shows that these values generally lie in the 11.9 to 13.6 range. There have been some lower values reported, but in most cases the log*ft* has been shown to be larger by more recent results.

The presently known second-forbidden transitions are listed, with references, in Table III. The transitions are divided into three groups according to the type of measurement which is most crucial for the log*ft* determination. In the first group are pure or nearly pure β emitters for which the half-life determination is of paramount importance. In the second group are cases where a weak, high-energy β group was studied with a β spectrometer. In the third group, the existence and intensity of the β or ϵ branch were inferred from γ-ray intensity imbalance.

In the first group, all 10 cases seem well established. The lowest value of log*ft* is 11.9 for ^{59}Ni, which decays by ϵ capture with $T_{1/2} = 7.5 \times 10^4$ yr to the ^{59}Co ground state. The second group of six cases contains low reported values of 9.7, 10.6, and 11.0. However, the 9.7 value for ^{95}Nb decay appears to be superseded by a later value of ≥ 10.8. The 10.6 value (^{95}Zr) does not seem experimentally well established. The 11.0 value for ^{59}Fe decay appears well established but a confirmation would be desirable.

In the third group, where the β or ϵ branch was inferred from γ-ray measurements, there are reported log*ft* values ranging from 7.2 to 13.6. However, the values in this group generally do not seem so well established as those in the first two groups. In particular, we feel that no case in this group may be used as convincing proof that a log*ft* value below 11.9 exists for a second-forbidden nonunique β transition. In some cases the possibility was not ruled out that unnoticed γ branches may account for part of the intensity imbalance, thus raising the log*ft* value.[30,31] We have elsewhere illustrated this point in the case of ^{24}Na decay (Ref. p in Table III); we do so again later in this paper in the case of ^{65}Ni and ^{144}Pm decays.

We propose the following rules: Strong rule – *second-forbidden β transitions have logft ≥ 11.0;*

TABLE V. Log*ft* values for highly forbidden β transitions (based on original literature surveyed before March 1972).

Initial nucleus → Final nucleus	Type of decay	$J^\pi_i \to J^\pi_f$	Log*ft* [a]	Reference
		(i) Third-forbidden nonunique ($\Delta J = 3$, parity change)		
^{87}Rb → ^{87}Sr	β^-	$\frac{3}{2}^- \to \frac{9}{2}^+$	17.6	b
		(ii) Third-forbidden unique ($\Delta J = 4$, parity change)		
^{40}K → ^{40}Ca	β^-	$4^- \to 0^+$	18.1 [c]	d
^{40}K → ^{40}Ar	β^+, ϵ	$4^- \to 0^+$	20.9 [c]	d
		(iii) Fourth-forbidden nonunique ($\Delta J = 4$, no parity change)		
^{96}Zr → ^{96}Nb	β^-	$0^+ \to 4^+$	>21.5	e
^{115}In → ^{115}Sn	β^-	$\frac{9}{2}^+ \to \frac{1}{2}^+$	22.6	f
^{113}Cd → ^{113}In	β^-	$\frac{1}{2}^+ \to \frac{9}{2}^+$	23.2	g
^{50}V → ^{50}Cr	β^-	$6^+ \to 2^+$	>23.2	h
^{50}V → ^{50}Ti	ϵ	$6^+ \to 2^+$	>23.2	h

[a] Calculated from the experimental information contained in the references cited. The Q values were obtained from A. H. Wapstra and N. B. Gove, Nucl. Data A9, 265 (1971).

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[c] Log*ft* values with third-forbidden corrections have been given by E. K. Warburton, G. T. Garvey, and I. S. Towner, Ann. Phys. (N.Y.) 57, 174 (1970).

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weak rule – second-forbidden β transitions have logft ⩾11.9. There are no well-established exceptions to the strong rule, one (^{59}Fe) to the weak rule.

E. Second-Forbidden Unique Transitions

The 11 known cases are shown in Table IV. The log*ft* values range from 12.8 to 18. The logf_2t values range from 13.8 to 15.6 except for the two ^{138}La values of ≈18. The large log*ft*≈ 18 values once led to an incorrect assignment of these β transitions as third forbidden and hence $J^\pi = 5^-$ for the ^{138}La ground state. However, the parity of the ^{138}La ground state has now been shown to be positive by DuBard, Sheline, and Ball (Ref. k in Table IV) from the $l_n = 2$ angular distribution for the ^{138}La-$(d,p)^{139}$La ground-state transition and from the known $\frac{7}{2}^+$ assignment for the ^{139}La ground state. These authors mention particle-phonon coupling in their discussion of the large log*ft* value.

Since there are no readily available published tables[32] giving second-forbidden correction factors, we formulate the following rule on the basis of log*ft* values: *Second-forbidden unique β transitions have logft ⩾12.8.*

F. Highly Forbidden β Transitions

The known cases are shown in Table V. These are very long-lived nuclei (the shortest, ^{40}K, has $T_{1/2} = 1.28\times10^9$ yr) with simple decay schemes.

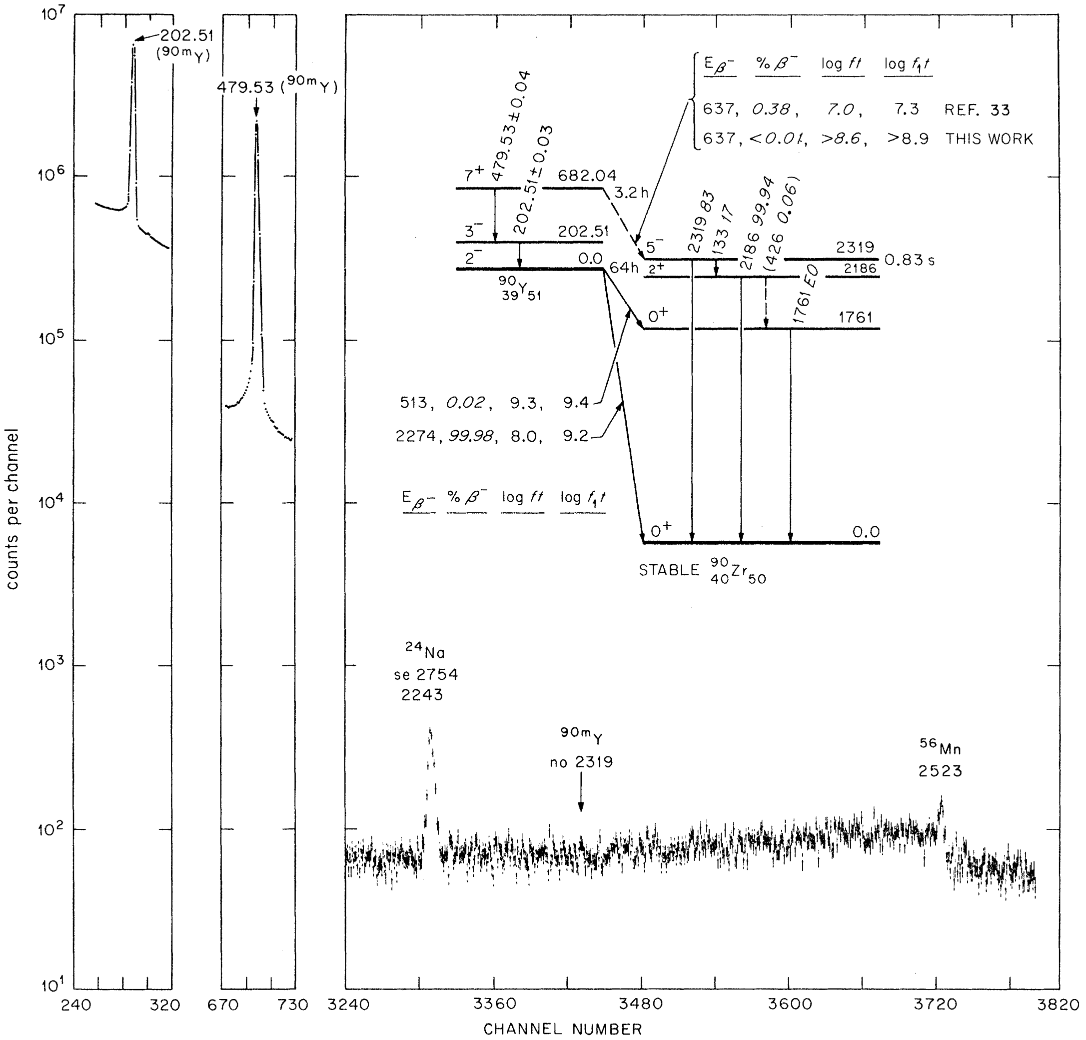

FIG. 2. Selected portions of γ-ray spectra (showing, in particular, the absence of the 2319-keV γ ray) obtained in 30 h with a 50-cm^3 Ge(Li) detector from six separate ^{90}Y sources produced by irradiating ^{89}Y with thermal neutrons. The inset shows the decay scheme incorporating our results in the scheme proposed in Ref. 34.

IV. EXPERIMENTAL RESULTS

A. Decay of ^{90m}Y

An 0.38% 637-keV β branch (see decay scheme shown in Fig. 2) was inferred by Davis, Kern, and Sheline[33] from the observation of the 2319-keV γ ray in ^{90m}Y decay. The corresponding $\log f_1 t$ value is 7.3. These measurements were done with a 3×3-in. NaI(Tl) crystal with sources produced by the ^{89}Y (d,p) reaction and subsequent ion-exchange separations. These authors also carried out half-life checks on the 2319-keV γ ray.

It is clear from Fig. 1 that $\log f_1 t = 7.3$ is anomalously low. We therefore reinvestigated the γ spectrum from ^{90m}Y with a 50-cm^3 Ge(Li) detector with a resolution (full width at half maximum) of 1.91 keV at 1.33 MeV. The sources were produced by thermal-neutron irradiation of ultra-pure ^{89}Y. Chemical separations were not attempted, since no trace elements were revealed in emission spectroscopy of the ^{89}Y sample. Selected portions of the γ spectrum are shown in Fig. 2.

We did not observe the 2319-keV γ ray reported by Davis, Kern, and Sheline.[33] Our intensity upper limit of 8×10^{-5} per decay of ^{90m}Y leads to $\log f_1 t > 8.9$ for the 637-keV β transition. To help visualize this upper intensity limit, a peak at 2319 keV in Fig. 2, with the general appearance of the 2523-keV peak, would have an intensity of 14×10^{-5} per ^{90m}Y decay.

The expected value for the photon intensity ratio $I(202.51\gamma)/I(479.53\gamma)$ is 1.059, if we assume the total conversion coefficients as 0.036 and 0.097 for the 202.51-keV ($M1+E2$, $\delta^2=0.2$) and the 479.53-keV ($M4$) γ rays, respectively.[34] The measured value is 1.037 ± 0.033.

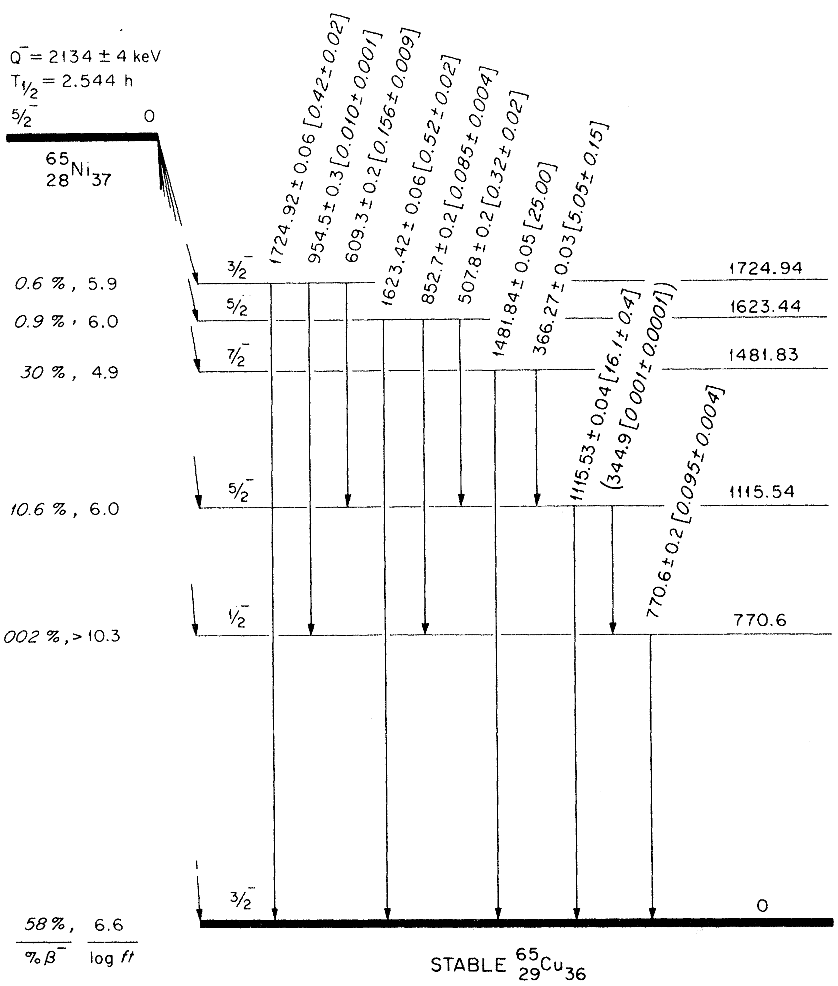

FIG. 3. Decay scheme of ^{65}Ni, basically similar to that proposed in Ref. 35, but incorporating our new results for γ energies and intensities. The 954.5-keV γ ray was sought in the present study.

B. Decay of ^{65}Ni

The decay scheme of ^{65}Ni is well established[35] and, in particular, the J^π assignments are certain. A second-forbidden β transition from the ^{65}Ni $\frac{5}{2}^-$ ground state to the 770.6-keV $\frac{1}{2}^-$ state in ^{65}Cu is energetically possible (see decay scheme shown in Fig. 3).

However, an expected $\log ft \geq 11.0$ implies $I_\beta \leq 0.0004\%$. Therefore, for all practical purposes, the intensity of γ transitions feeding the 770.6-keV level should equal the intensity of the 770.6-keV γ ray. Indeed, Cline and Heath[36] obtained absolute intensity values of $(0.08 \pm 0.03)\%$ for both the 852.7- and 770.6-keV γ rays.

We measured the γ spectrum of ^{65}Ni sources produced by thermal-neutron irradiation of 97.9% enriched ^{64}Ni. The Ge(Li) detector efficiency calibrations were carried out with fresh (1972) International Atomic Energy Agency (IAEA) sources supplemented by the γ radiations from ^{226}Ra[37] and from ^{82}Br.[38]

Our initial measurements suggested that the $\frac{5}{2}^- \rightarrow \frac{1}{2}^-$ β transition might have, contrary to our expectations, a low $\log ft$ value. We obtained intensity of 0.085% for the 852.7-keV γ ray and 0.095% for the 770.6-keV γ ray leaving an imbalance of $(0.010 \pm 0.003)\%$ ($\log ft = 9.55 \pm 0.15$). A weak 344.9-keV γ ray, unobserved by us but known to deexcite the 1115.54-keV level[39] is inadequate to absorb the missing intensity.

Our $\log ft$ rule would then assert that there is a missing γ ray which in the present case happens to be the 954.5-keV γ ray. Our observation of this

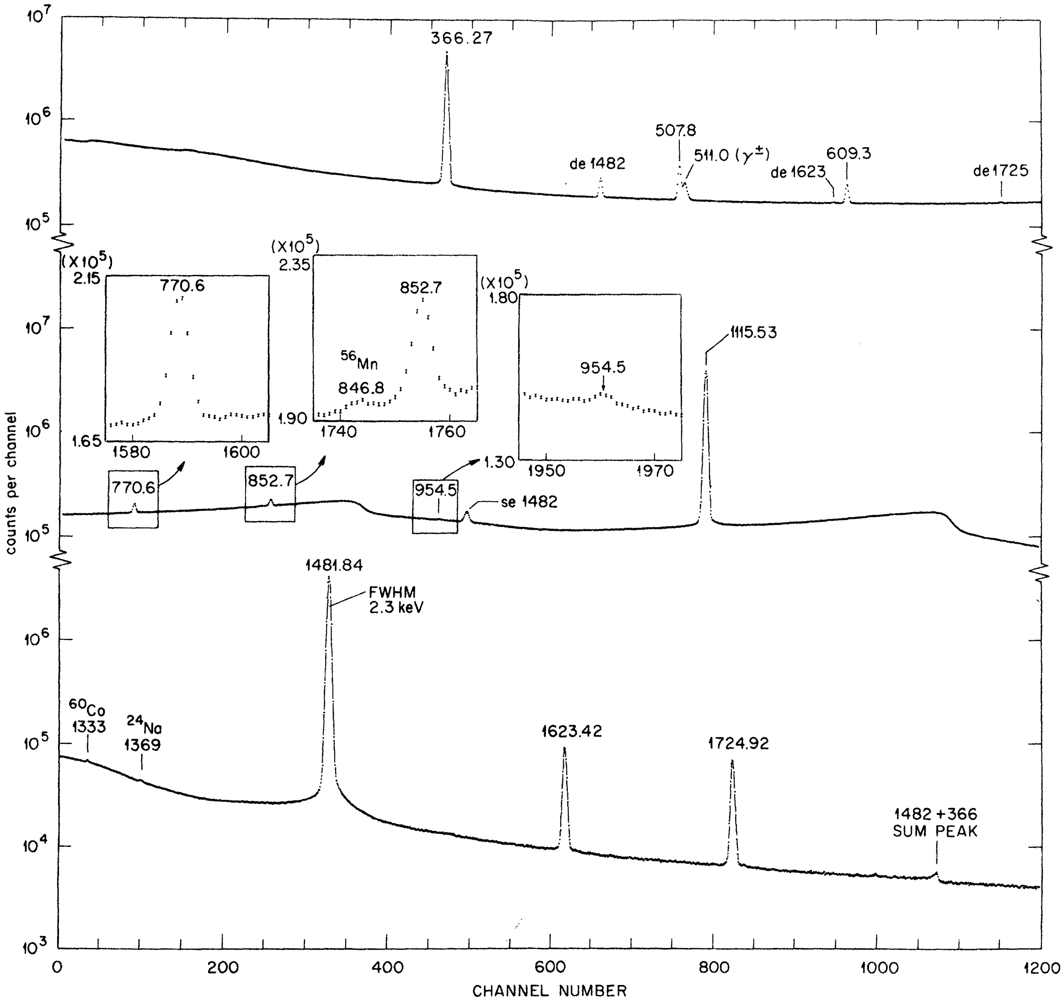

FIG. 4. γ-ray spectra (showing, in particular, the 954.5-keV γ ray) obtained in 30 h with a 50-cm^3 Ge(Li) detector from eight separate ^{65}Ni sources produced by irradiating ^{64}Ni with thermal neutrons.

γ ray through long periods of counting is shown in Fig. 4. If the intensity of the 770.6-keV γ ray is taken as 1000 units, we obtain 895 ± 18, 106 ± 11, and 10 ± 1 units for the intensities of the 853-, 954-, and 345-keV γ rays. The intensity of the γ rays (justifiably neglecting internal conversion) feeding the 770.6-keV level is 1011 ± 22 units, thus confirming our original conjecture of nearly zero direct β feeding to the 770.6-keV level.

C. Decay of ^{144}Pm

The main features of the ^{144}Pm decay scheme are well known.[40, 41] We remeasured the γ spectrum of ^{144}Pm (see Fig. 5) with sources produced by the ^{145}Nd$(p, 2n)$ reaction and subsequent ion-exchange separations. We paid special attention to the possible presence of weak, high-energy γ transitions. Through detailed analysis, taking

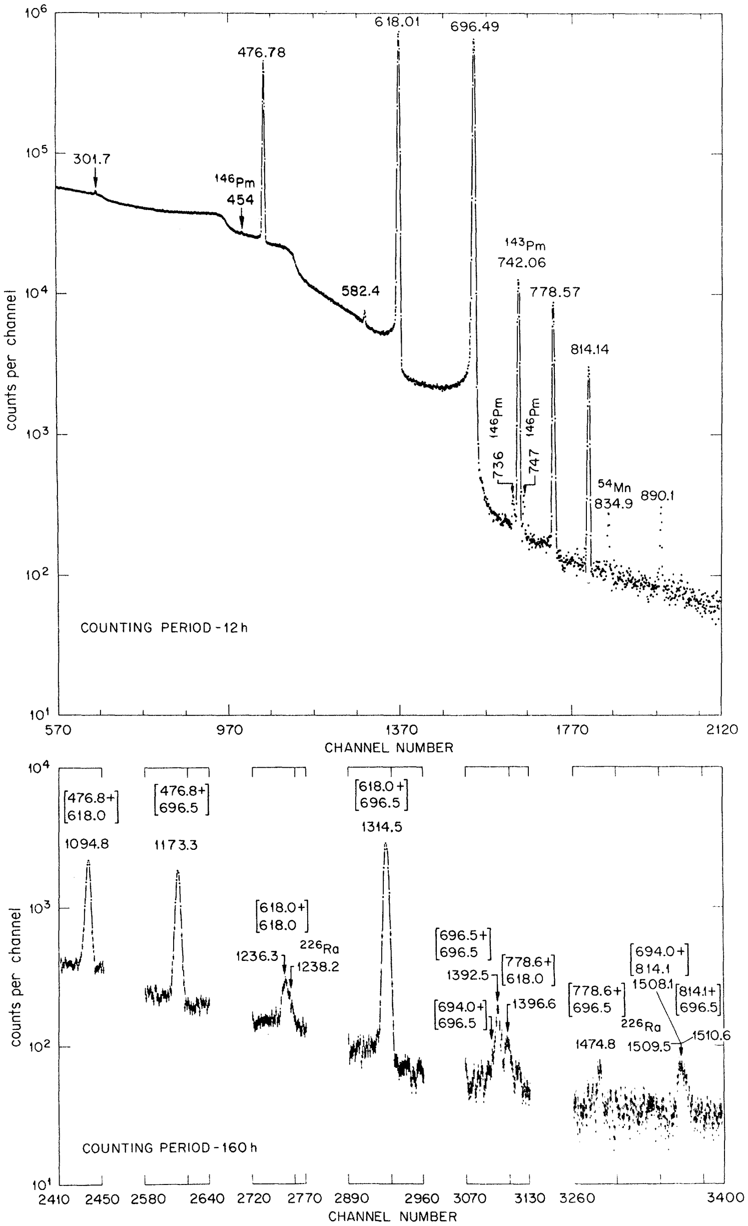

FIG. 5. Decay scheme of ^{144}Pm, basically similar to that proposed in Ref. 40, but incorporating our new results for γ energies and intensities. The 694.0-keV γ ray was sought in the present study.

especially into account angular-correlation effects,[42] we confirmed that the peaks at 1094.8, 1173.3, 1314.5, and 1474.8 keV were genuine sum peaks. The peaks at 1396.6 and 1510 keV were, on the other hand, larger than expected from summing effects alone. From our data, we extracted an intensity value for the 1396.6-keV γ ray but the analysis of the 1510-keV multiplet was complicated by the presence of the 1509.5-keV γ ray from ^{226}Ra which was present as room background and which accounted for approximately a third of the peak intensity. We feel that γ rays of energies 1508.1 and 1510.6 keV (see decay scheme shown in Fig. 6) are present but can set only upper intensity limits.

The 3^- assignment to the 1510.64-keV level is based on recent angular correlation measurements,[43] the strong excitation of this level in (d,d'),[44] and the $E1$ multipolarity assignment[45, 46] for the 814.14-keV γ ray. The J^π assignments for the remaining levels have already been discussed.[40]

With reference to Fig. 6, it is clear that were it not for the presence of the 694.0-keV γ ray, intensity balance requirements at the 1510.64-keV level would suggest the presence of an 0.3% electron-capture branch feeding this level from the ground state of ^{144}Pm. Such an ϵ branch would have an untenably low logft value of 10.6.

The results of our search for the crucial 694.0-keV γ ray are shown in Fig. 7. The coincidence measurements, necessitated by the proximity of the 694.0-keV γ ray to the very intense 696.5-keV γ ray, were carried out with the ^{144}Pm source sandwiched between two Ge(Li) detectors. The 618.0-keV γ ray, though not in coincidence with the 814.1-keV γ ray, is present in the coincidence spectrum because the gate accepts (Compton 476.8γ) + (Compton 696.5γ) events.

The intensity value quoted in Fig. 6 for the 694.0-keV γ ray is that obtained from the 180° coincidence data and hence not corrected for angular correlation. Therefore, we have doubled the quoted uncertainty for the 694.0-keV γ-ray intensity in order to estimate the maximum ϵ intensity to the 1510-keV level. The possible presence of a 196.1-keV γ ray between the 1510.64- and 1314.59-keV levels has been neglected since we have deter-

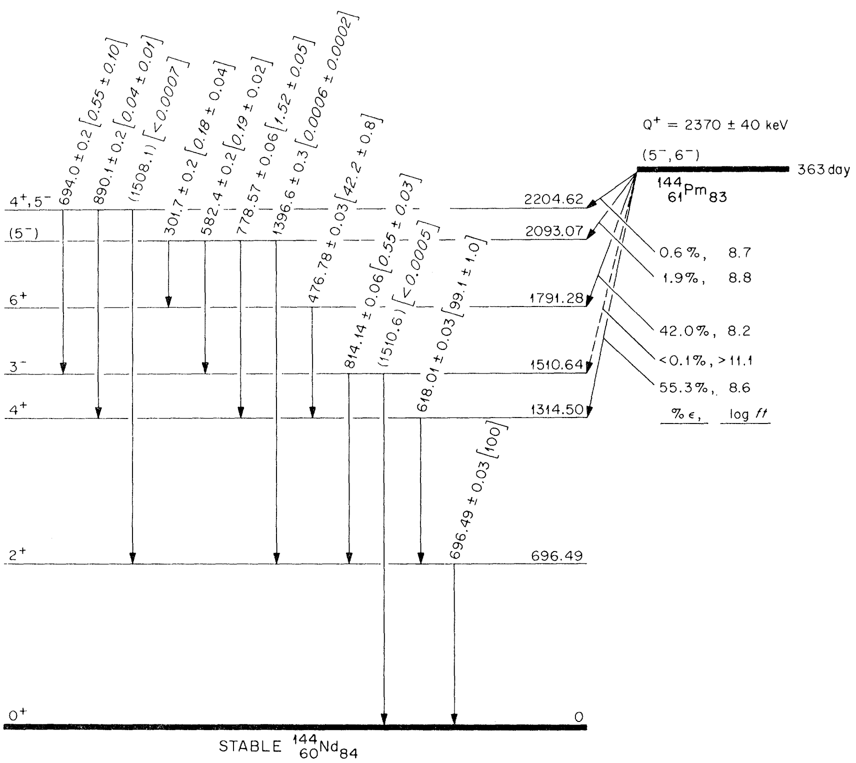

FIG. 6. Selected portions of γ-ray spectra obtained with a 50-cm^3 Ge(Li) detector from ^{144}Pm sources produced by the ^{145}Nd$(p,2n)$ reaction. The source-to-detector distance was 15 cm. The 1474.8-keV peak was found to be a 778.6 +696.5-keV sum peak, but the peaks at 1396.6 and 1510 keV were larger than expected from summing effects alone and hence indicated the presence of γ rays.

mined $I(196.1\gamma)/I(814.1\gamma) < 0.02$ from separate ^{143}Nd(n,γ) measurements.[47] The resulting logft > 11.1 leaves the proposed rules intact.

V. SUMMARY

Classification of β transitions into narrow and non-overlapping bins based on logft values, indeed, seems hopeless.[48] It is conceivable that at some future date our understanding of nuclear structure and β-decay interaction will have reached a point that each and every logft value can be satisfactorily explained. Meanwhile, if the lower limit in logft value for a particular forbiddenness category can be reliably established, a new β transition of lower logft value can be safely assigned to a forbiddenness category of lower order. Theoretical calculations of logft limits are not available but some empirical rules may be postulated from the present survey.

We summarize below our main conclusions and rephrase them for direct application to J^π assignments. We let ΔJ denote the difference in spin between the initial and final states. Similarly, we let $\Delta\pi = +$ denote same parity and $\Delta\pi = -$ different parity between the initial and final states.

Rule 1. For $Z < 80$, if log$ft < 5.9$, $\Delta J = 0, 1$; $\Delta\pi = +$. For $Z \geq 80$, if log$ft < 5.1$, $\Delta J = 0, 1$; $\Delta\pi = +$. If $3.6 < \log ft < 5.9$, and if one of the states has $J^\pi = 0^+$, the other has $J^\pi = 1^+$.

Rule 2. If log$f_1t < 8.5$, $\Delta J = 0, 1$; $\Delta\pi = \pm$.

Rule 3. If log$ft < 11.0$, $\Delta J = 0, 1$; $\Delta\pi = \pm$ or $\Delta J = 2$, $\Delta\pi = -$.

Rule 4. If log$ft < 12.8$, $\Delta J = 0, 1, 2$; $\Delta\pi = \pm$.

These rules are shown schematically in Fig. 8. Since these rules are designed to permit definite spin and parity assignments (those usually given without parentheses), any exception would severe-

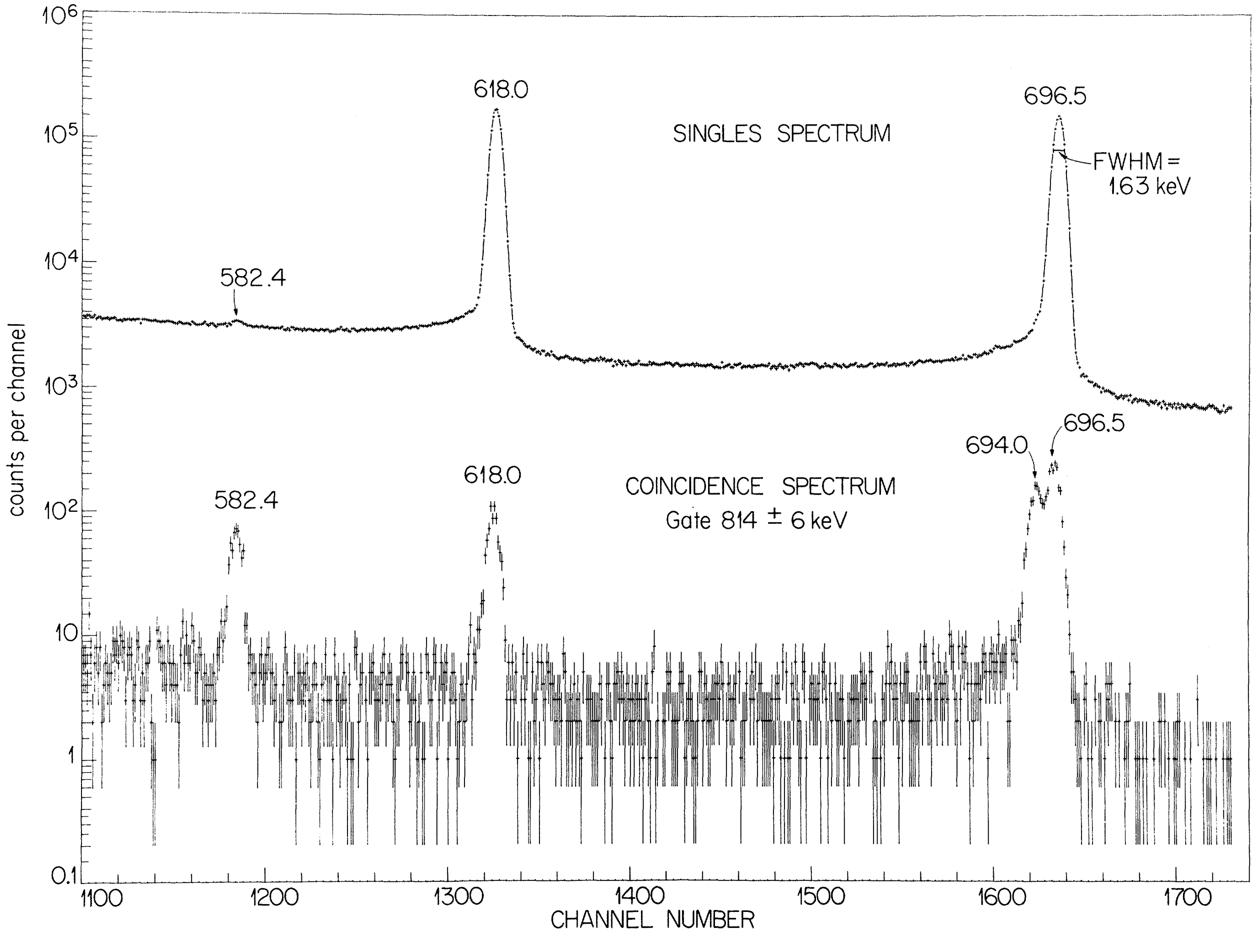

FIG. 7. Selected portions of direct and coincident γ-ray spectra obtained with a 25-cm^3 Ge(Li) detector from ^{144}Pm. The 814 ± 6-keV gate was selected by another 40-cm^3 Ge(Li) detector. The 180° coincidence measurements lasting 7 day were undertaken in search of the 694.0-keV γ ray.

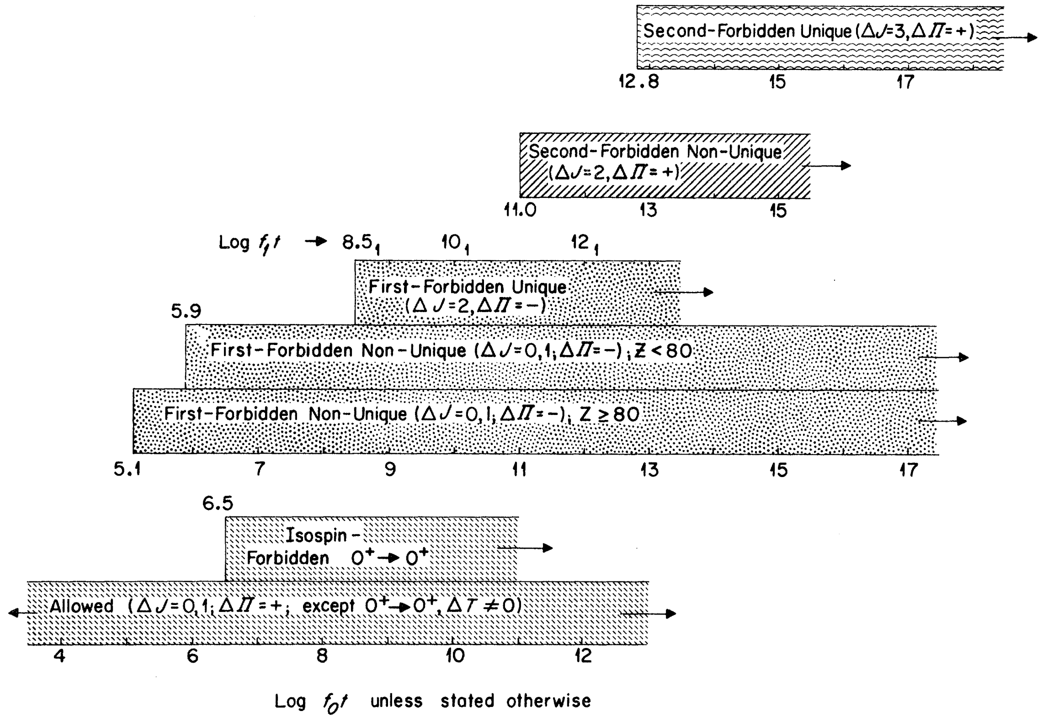

FIG. 8. Permissible ranges of logft values based on empirical evidence.

ly limit the usefulness of the corresponding rule. The results of our study indicate that many reported low logft values have not withstood subsequent closer scrutiny. Therefore, we feel that a decay scheme purported to contain a violation should be carefully examined to check all aspects (correction for internal conversion, J^π assignments, Q value, missing γ rays, etc.) which may affect the logft value or the forbiddenness category.

VI. ACKNOWLEDGMENTS

The past and present members of the Nuclear Data Project at the Oak Ridge National Laboratory have contributed in great measure to the present work. A systematic collection of logft data, including all allowed and first-forbidden cases, is in progress and was begun by Dr. A. Artna-Cohen. The formulas for computing logft values were developed by Dr. M. J. Martin. Dr. E. K. Warburton offered several helpful comments and criticisms. Finally, the present work was greatly influenced by Dr. K. Way, who started and for many years guided the Nuclear Data Project and whose interest in compilation and systematics has been a major factor in the development of nuclear structure physics.

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