Beta decay of ^{39}Cl

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The β decay of ^{39}Cl, produced in the ^{37}Cl(t,p)^{39}Cl reaction at $E_t=3.1$ MeV, has been investigated with a Ge-NaI(Tl) Compton-suppression γ-ray spectrometer. Nineteen γ-ray transitions were observed, including 10 previously known. Precision energy measurements were carried out on six of the strongest lines. In the proposed decay scheme a weak new β-ray branch is established to the 2950-keV level of ^{39}Ar, and the populations of ^{39}Ar levels at 2093 and 2433 keV are accounted for by γ-ray decays from higher excited states. Spin-parity assignments are given.

I. INTRODUCTION

Only two previous studies[1,2] have been made of the β decay of the $J^\pi=\frac{3}{2}^+$ ground state of ^{39}Cl [$T_{1/2}=55.6(2)$ min (Ref. 3)], the more recent being that of Engelbertink, Warburton, and Olness in 1972. Samples produced in the ^{37}Cl(t,p)^{39}Cl reaction at $E_t=3.0$ MeV were measured[2] with Ge(Li) and NaI(Tl) detectors in singles and in coincidence. A decay scheme was proposed that included 10 γ-ray transitions and involved six excited states of ^{39}Ar. Among the unanswered questions was that γ rays of 2093 keV were observed, but that the formation of the $\frac{5}{2}^-$ 2093-keV level appeared to be too intense to be accounted for by first-forbidden β^- decay, and γ-ray feeding of this state was not observed.

Our interest in a reinvestigation of ^{39}Cl(β^-)^{39}Ar was stimulated by calculations simultaneously underway on the structure of ^{39}Ar, reported in the following article.[4] That work utilizes the recently developed spherical shell-model interaction SDPF which uses a full $(2s,1d,1f,2p)$ configuration space.[5] Since ^{39}Cl has $N,Z=22,17$ the allowed Gamow-Teller (GT) beta decay ^{39}Cl(β^-)^{39}Ar (see Fig. 3) should be describable within the model space ^{16}O$(2s,1d)^{21}(1f,2p)^2$ and as such can be calculated with the SDPF interaction.

The first-forbidden β^- decay modes of ^{39}Cl involve in lowest order transitions to states within the ^{16}O$(2s,1d)^{22}$ $(1f,2p)^1$ configuration. The formalism necessary to calculate nonunique first-forbidden decays in the $A\sim 40$ mass region was recently developed[6] for use with the SDPF interaction and interest in such decays from ^{39}Cl was therefore aroused.

The present experimental work reveals further details of the ^{39}Cl decay scheme, answers some of the previous questions, and forms the basis for comparison with the theoretical calculations.[4] As part of our ongoing program of precision γ-ray energy determinations (see, e.g., Refs. 5 and 7), such measurements were made for ^{39}Ar γ transitions via ^{39}Cl(β^-)^{39}Ar.

II. EXPERIMENTAL METHODS

Sources of ^{39}Cl were produced in the ^{37}Cl(t,p)^{39}Cl reaction at $E_t=3.1$ MeV by Van de Graaff bombardment of Ba^{37}Cl$_2$ targets enriched to 90.4% in ^{37}Cl. The powder samples were deposited as a slurry on thick Ta backings, and the beam currents were generally ~ 150 nA for 1 h. After bombardment, the powder was scraped off the Ta backing into a small plastic bottle and then transferred to the detector in a fixed geometry. The detector was a Ge-Na(Tl) Compton-suppression spectrometer including an intrinsic Ge detector with an efficiency at 1.33 MeV of 30% relative to a 7.65×7.65-cm NaI(Tl) detector, and a resolution [full width at half maximum (FWHM)] of 2.0 keV at that energy.

To study the complete γ-ray spectrum, each bombardment was made on a fresh target and measurements were made in a pulse-height analyzer during four successive 1-h runs, each separately recorded on tape. Previously unobserved transitions could then be assigned to ^{39}Cl decay partially on the basis of their decay rates. Results from different bombardments were combined after making small gain-shift corrections.

The γ-ray efficiency versus E_γ was measured with ^{56}Co and ^{152}Eu sources, following standard techniques. An important part of the analysis was to establish the γ-ray summing corrections in order to distinguish between real γ-ray transitions and the summing effects of strong cascade γ rays. At the two source-to-detector distances used, i.e., $d=7.0$ and 14.0 cm, a ^{60}Co source was counted and the intensity of the 2506-keV sum peak was determined relative to the 1173- and 1333-keV photopeaks. At $d=7.0$ cm the results were $I_{\rm sum}/I_{1173}=2.60\times 10^{-3}$ and $I_{\rm sum}/I_{1333}=2.85\times 10^{-3}$, while at $d=14.0$ cm we obtained $I_{\rm sum}/I_{1173}=8.4\times 10^{-4}$ and $I_{\rm sum}/I_{1333}=9.3\times 10^{-4}$. Uncertainties in all of these ratios were less than $\pm 5\%$. Extrapolations from these values could be used to calculate the amounts of summing expected for various cascade pairs of γ rays in ^{39}Cl decay.

TABLE I. Gamma-ray energies, relative intensities, and branching ratios (BR) in ^{39}Cl$(\beta^-)^{39}$Ar.

J_i^π	^{39}Ar level E_i (keV)	E_f (keV)	E_γ (keV)	Intensity[a] (relative)	BR (%)[b] Present	Ref. 3	Adopted
$\frac{3}{2}^-$	1267.207(8)	0	1267.191(11)[c]	10 000	100	100	100
$\frac{3}{2}^+$	1517.540(8)	1267	250.333(3)[c]	8630(300)	54.1(10)	54.1(12)	54.1(8)
		0	1517.498(10)[c]	7320(160)	45.9(10)	45.9(12)	45.9(8)
$\frac{5}{2}^-$	2092.749(20)	1267	825.533	1.7(8)	8.9(38)	3.9(8)	4.1(10)
		0	2092.738(30)	17.3(4)	91.1(38)	96.1(8)	95.9(10)
$(\frac{5}{2}^-,\frac{7}{2},\frac{9}{2}^-)$	2342.2(2)	0	2342.1	<0.2		100	100
$\frac{1}{2}^+$	2358.282(11)	1518	840.775(25)	24.8(6)	5.2(2)	3(1)	5.1(4)
		1267	1091.056(8)[c]	451(9)	94.8(2)	97(1)	94.9(4)
		0	2358.205	<1	<0.2	<0.3	<0.2
$\frac{3}{2}^-$	2433.48(3)	1518	915.86(10)	1.0(7)	11(7)	5.3(15)	5.6(15)
		1267	1166.250(50)	5.71(46)	65(6)	70.7(9)	70.7(9)
		0	2433.488(80)	2.08(13)	24(3)	23.8(9)	23.7(9)
$\frac{7}{2}^-$	2481.49(13)	0	2481.41	<0.4		82.5(6)	82.5(6)
$(\frac{3}{2},\frac{5}{2})^+$	2503.417(11)	2093	410.690(20)	17.9(4)	4.3(2)	<7	4.3(2)
		1518	985.861(9)[c]	390(7)	92.8(2)	94(2)	92.8(2)
		1267	1236.190(50)	11.2(5)	2.7(2)	6(2)	2.7(2)
		0	2503.275(70)	1.0(1)	0.24(3)	<0.3	0.24(3)
$(\frac{5}{2}^-,\frac{7}{2},\frac{9}{2}^-)$	2523.74(17)	0	2523.65	<0.3		100	100
$\frac{3}{2}^-$	2631.56(15)	2093	538.6	<0.4		81(2)	81(2)
$\frac{11}{2}^-$	2651.1(3)	0	2651.0	<0.2		100	100
$\frac{5}{2}^-$	2755.5(3)	0	2755.4	<0.5		56.3(14)	56.3(14)
$\frac{1}{2}^+$	2829.935(20)	2632	198.38	<0.5	<0.5		<0.5
		2524	306.21	<0.3	<0.3	<0.5	<0.3
		2503	326.52	<3.0	<2.8	<1.1	<1.1
		2433	396.462(40)	8.2(3)	7.5(3)		7.5(3)
		2358	471.65	<1.5	<1.4	<7.0	<1.4
		1518	1312.360(20)[c]	46.9(11)	43.0(8)	46.3(13)	42.8(8)
		1267	1562.704(25)	53.5(12)	49.0(8)	58.7(13)	49.2(8)
		0	2830.22(40)	<0.3	<0.25	<1.3	<0.25
$(\frac{3}{2}^+,\frac{5}{2})$	2949.95(10)	2503	446.61(13)	2.56(50)	52(6)	51.4(10)	51.4(10)
		1518	1432.27(15)	2.40(30)	48(6)	48.6(10)	48.6(10)
$\frac{1}{2}^+$	3287.0(4)	1267	2019.7	<0.7		100	100

[a]Limits correspond to two standard deviations.
[b]The adopted values for upper limits are the smaller of the two values.
[c]Value from precision energy measurements.

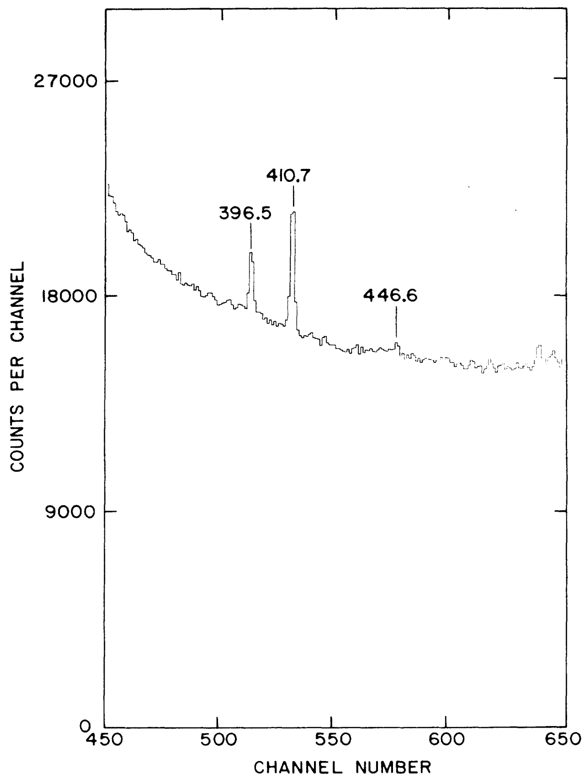

FIG. 1. Portion of the γ-ray spectrum from the decay of ^{39}Cl showing newly observed γ rays of 396.5, 410.7, and 446.6 keV.

Precision energy measurements were made on six of the ^{39}Cl γ rays at high dispersion and with various digital offsets, following previously developed techniques.[5,7] Energy calibration sources included ^{152}Eu, ^{22}Na, ^{110}Ag^m, and ^{207}Bi. In addition to mixed-source runs, separate measurements on ^{39}Cl and on each calibration source were made in order to check the individual spectra for weak γ-ray peaks that might occur in the vicinity of the lines being compared. In a given sequence of runs on a single source the precision E_γ measurements consisted of first comparing the γ rays in the 900–1500 keV range with the ^{22}Na, ^{110}Ag^m, and ^{207}Bi sources, in four or five runs of $\sim$25 min each, at various gain settings, and with a 6 mm thick Pb absorber in place. The absorber was then removed and another four or five runs of 25 min each were made comparing the 250-keV γ ray from ^{39}Cl decay with the 244- and 344-keV γ rays from ^{152}Eu. Results of the precision E_γ determinations, indicated in Table I, are each based on a total of 14–17 comparison measurements with the standard sources.

III. RESULTS

A. Gamma-ray energies and branching ratios

Final data on the complete γ-ray spectrum were obtained at $d=7.0$ cm with three sources, measured for a combined total of 12 h. Portions of the summed spectrum are shown in Figs. 1 and 2. In Fig. 1 peaks are identified at 396.5, 410.7, and 446.6 keV that decay with the ^{39}Cl half-life. They were not observed in the previous

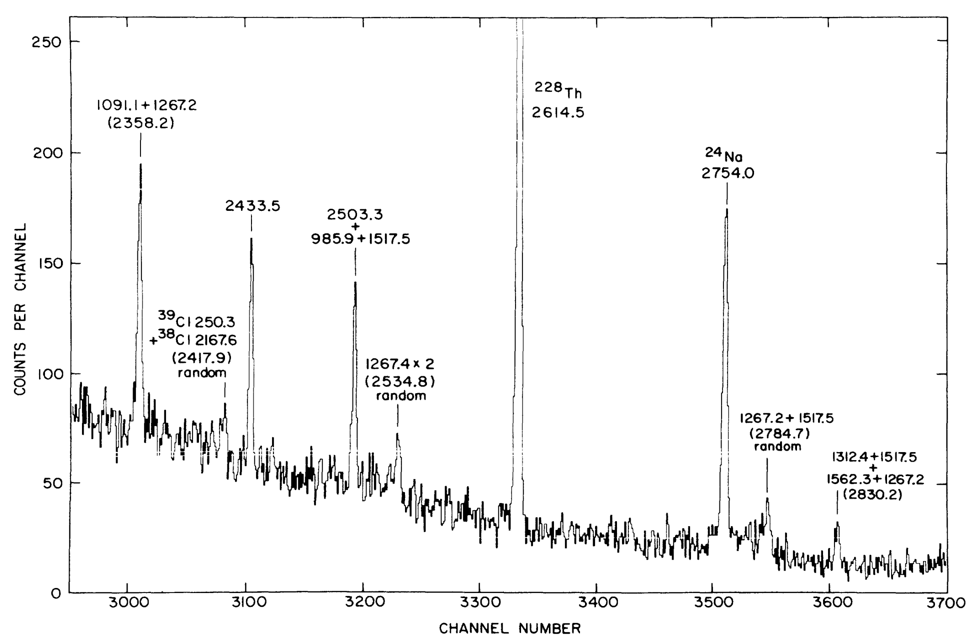

FIG. 2. Region of the ^{39}Cl γ-ray spectrum above 2.3 MeV. Various peaks (identified by their energies in keV) are discussed in the text.

TABLE II. β-ray branches, $\log f_0 t$ values, and Gamow-Teller (B_0) and unique first-forbidden (B_1) transition strengths in the decay of ^{39}Cl ($J^\pi = \frac{3}{2}^+$).

J^π	E_x (keV)	β branch (%)	$\log f_0 t$	Order[a] (n)	B_n[b] (fm^{2n})
$\frac{7}{2}^-$	0	7(2)	7.82(12)	1	1.3(4)
$\frac{3}{2}^-$	1267	4.5(16)	7.14(16)	nu	$f=8.3(30)\times10^{-2}$
$\frac{3}{2}^+$	1518	83.1(22)	5.65(2)	0	$13.74(6)\times10^{-3}$
$\frac{1}{2}^+$	2358	2.56(5)	6.15(3)	0	$4.34(32)\times10^{-3}$
$(\frac{3}{2},\frac{5}{2})^+$	2503	2.24(4)	5.97(4)	0	$6.68(54)\times10^{-3}$
$\frac{1}{2}^+$	2829	0.59(1)	5.84(5)	0	$8.85(97)\times10^{-3}$
$(\frac{3}{2}^+,\frac{5}{2})$	2950	$26.6(32)\times10^{-3}$	6.84(8)	0[c]	$0.88(15)\times10^{-3}$
$\frac{5}{2}^-$	2093	$<8.6\times10^{-3}$	>8.9	nu	$f<1.6\times10^{-4}$
$(\frac{5}{2}^-,\frac{7}{2},\frac{9}{2}^-)$	2342	$<1.2\times10^{-3}$	>9.5	1, 2, or 3	<0.2[d]
$\frac{3}{2}^-$	2433	$<6.2\times10^{-3}$	>8.6	nu	$f<1.1\times10^{-4}$
$\frac{7}{2}^-$	2481	$<2.3\times10^{-3}$	>8.9	1	<0.8
$(\frac{5}{2}^-,\frac{7}{2},\frac{9}{2}^-)$	2523	$<1.7\times10^{-3}$	>9.0	1, 2, or 3	<0.8[d]
$\frac{3}{2}^-$	2631	$<2.9\times10^{-3}$	>8.6	nu	$f<5.3\times10^{-5}$
$\frac{11}{2}^-$	2651	$<1.2\times10^{-3}$	>8.9	3	
$\frac{5}{2}^-$	2756	$<5.2\times10^{-3}$	>8.1	nu	$f<9.6\times10^{-5}$
$\frac{1}{2}^+$	3287	$<4.0\times10^{-3}$	>5.8	0	$<10\times10^{-3}$

[a]The degree of forbiddenness; nu denotes nonunique first forbidden.
[b]Allowed Gamow-Teller ($n=0$) and first-forbidden unique ($n=1$) transition strengths (matrix element squared).
[c]Assumed.
[d]This is the limit on B_1 in the event that $J^\pi = \frac{7}{2}^-$.

work[2] because of the relatively high Compton continuum. In the region above 2.3 MeV, shown in Fig. 2, the numerous peaks have all been identified. The only real γ rays in the figure belonging to ^{39}Cl decay are those at 2433.5 and 2503.3 keV. About half of the latter peak is actually due to 985.9 + 1517.5 summing at $d=7.0$ cm. The net intensity of the real 2503.3-keV γ ray was confirmed in the run at $d=14.0$ cm. Aside from the ^{228}Th and ^{24}Na γ rays, all of the other peaks in Fig. 2 are due to either real or random summing of ^{39}Cl (or in one case, ^{39}Cl + ^{38}Cl) γ rays.

The results of the γ-ray measurements are summarized in Tables I and II and in the decay scheme of Fig. 3. We first consider Table I. Those E_γ with uncertainties attached are our measurements. Those without uncertainties were calculated from the level energies. Energies of levels from which γ decays were observed were calculated from a least squares fit to all measured γ energies assuming the level scheme of Fig. 3. Energies of levels for which no γ decay was observed are from Ref. 3. Limits on γ-ray intensities correspond to two standard deviations. The J^π assignments are from Ref. 3 or are discussed in the following paper.[4] There are no serious discrepancies with previous work. We observed nine γ rays not seen previously in ^{39}Cl β^- decay. The 447- and 1432-keV γ rays are associated with the decay of the ^{39}Ar 2950-keV level and the β branch to this level is the only new one resulting from this study. Three of the other seven new γ rays (i.e., 411, 826, and 2503 keV) represent new γ branches connecting ^{39}Ar levels previously known to be fed by ^{39}Cl β^-. The 411-keV γ ray is assigned as 2503→2093 and explains the bulk of the 2093-keV intensity, as discussed in the Introduction. The 826-keV γ ray is assigned as 2093→1267, and the 2503-keV transition is a weak ground-state decay. The remaining four new γ rays (i.e., 396, 916, 1166, and 2433 keV) are associated with the newly observed 396-keV 2830→2433 transition and the subsequent decay of the 2433-keV level.

B. β^- branching ratios, $\log ft$ values, and matrix elements

The γ-ray intensities of Table I and the decay scheme of Fig. 3 result in the β^- branching ratios of Table II. These branches result from the listed γ intensities of Table I with two exceptions. The poorly determined intensities for the 2093→1267 and 2433→1518 transitions were calculated from the intensities of the more intense branches and the adopted γ-ray branching ratios; i.e., use was made of previous information for these decay modes.

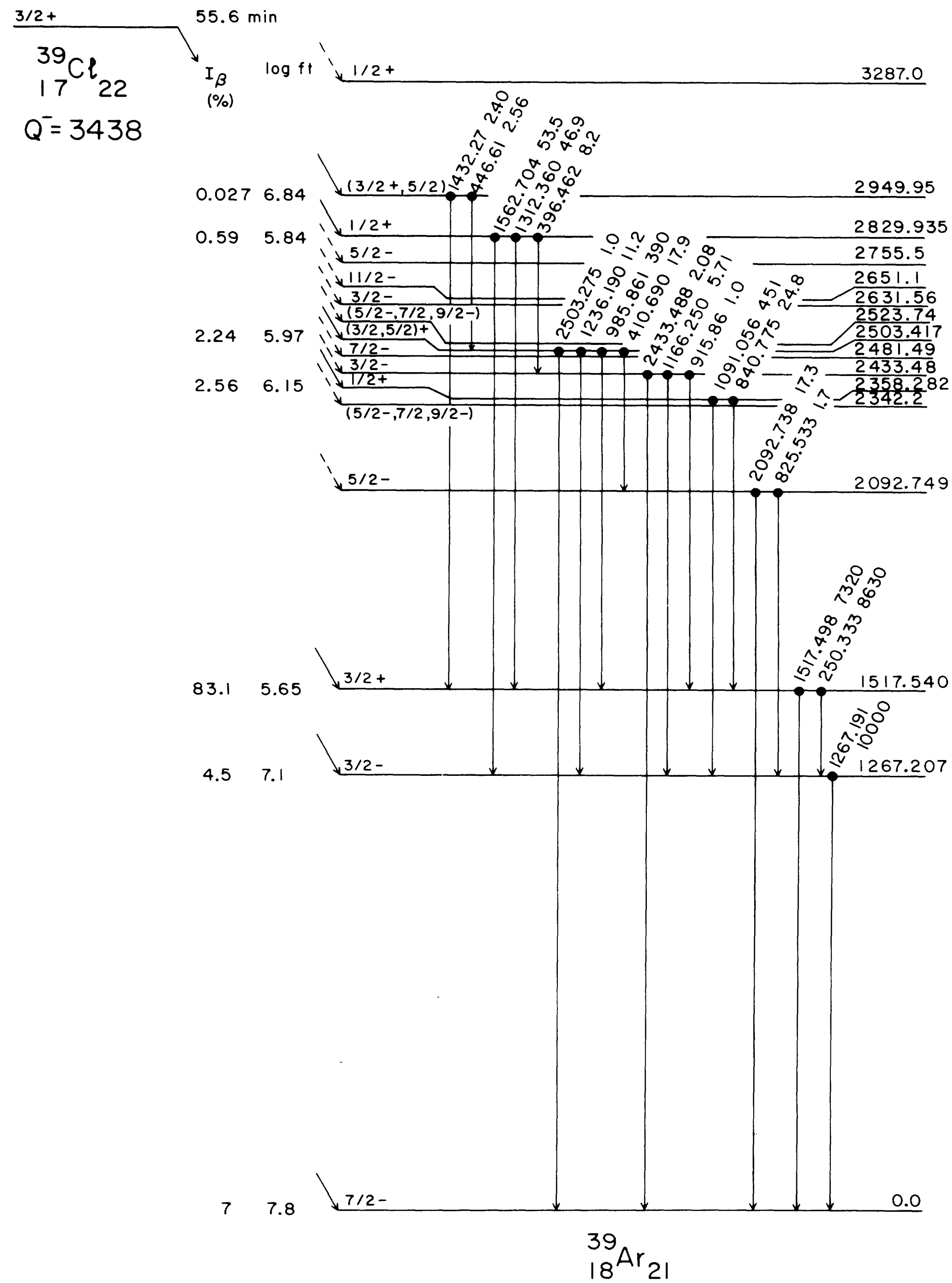

FIG. 3. Proposed decay scheme of ^{39}Cl. All energies are in keV and γ-ray intensities are given relative to $I_{1267\gamma}=10\,000$. For the ^{39}Ar levels shown, but not directly fed in ^{39}Cl decay, β-ray branching and logft limits are given in Table II.

The β^- branch into the ground state is from the work of Penning *et al.*[1]

The logft values of Table II were calculated assuming allowed decay, $Q(\beta^-)=3438(18)$ keV, $T_{1/2}=3336(12)$ s, and the excitation energies of Table I.

The transition strengths (matrix element squared) for allowed Gamow-Teller ($n=0$) and unique first-forbidden ($n=1$) decay are defined by[5]

$$B_n=6166\left\{\frac{[(2n+1)!!]^2}{(2n+1)}\right\}\lambda\!\!\!^{-}{}_{\mathrm{Ce}}^{2n}(f_nt)^{-1}\,, \quad (1)$$

where $2\pi\lambda\!\!\!^{-}{}_{\mathrm{Ce}}$ is the Compton wavelength of the electron ($\lambda\!\!\!^{-}{}_{\mathrm{Ce}}=386.159$ fm). Equation (1) gives

$$B_0=6166/f_0t,\quad 10^{-6}B_1=2758/f_1t\ \mathrm{fm}^2\,, \quad (2)$$

where f_0 and f_1 are the Fermi functions calculated with shape factors of unity and $\sim\frac{1}{12}(p^2+q^2)$, respectively. For nonunique first-forbidden decay (designated by nu in column 5 of Table II) comparison to experiment is conventionally made via the f value, which is defined experimentally by $f=6166/t_p$, where t_p is the partial half-life of the β^- branch in question (see Ref. 8).

A comparison of the experimental results with theoretical calculations is given in the following paper.[4]

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