Fermi Beta Decay, $A > 40$: The Masses of ^{42}Sc, ^{46}V, ^{50}Mn, and ^{54}Co

J. C. Hardy, G. C. Ball, J. S. Geiger, R. L. Graham, J. A. Macdonald, and H. Schmeing
Atomic Energy of Canada Limited, Physics Division, Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada K0J 1J0
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The Q values for (^{3}He,t) reactions on ^{26}Mg, ^{34}S, ^{42}Ca, ^{46}Ti, ^{50}Cr, and ^{54}Fe have been measured relative to that for ^{27}Al(^{3}He,t)^{27}Si. The results lead to significant deviations from previously accepted values for the β-decay end-point energies of ^{42}Sc, ^{46}V, and ^{54}Co. The new ft values for these transitions now agree with other known superallowed transitions ($A < 40$); only the decay of ^{50}Mn remains anomalous. A limit is also set on the $Z^2\alpha^2$ radiative correction term.

There are nine superallowed $0^+ \rightarrow 0^+$ β transitions whose ft values have been determined with an accuracy better than $\pm 1\%$. The lightest parent nucleus in this group is ^{14}O; the heaviest is ^{54}Co. Ideally, the ft values for all nine transitions should be identical to the extent that radiative corrections and charge-dependent mixing can be properly accounted for. If such self-consistency were established, then the average ft value would determine the vector coupling constant of nuclear β decay and would contribute to a stringent test of of Cabibbo theory through comparison with corresponding values obtained for decay of the μ and K^+ mesons.

Until now, this picture has been clouded by the fact that, while the five transitions between nuclei with $A < 40$ were consistent with one another, the ft values for the decays of ^{42}Sc, ^{46}V, ^{50}Mn, and ^{54}Co were significantly higher even after the calculated corrections had been applied.[1] This has caused doubt in the accuracy of the corrections and ultimately in the reliability of the vector coupling constant. We have remeasured the transition energies, upon which the statistical rate functions f depend, for six of these transitions, including all four between nuclei with $A > 40$. Our results for ^{42}Sc, ^{46}V, and ^{54}Co indicate a considerable change from the previously accepted decay energies, with the result that the ft values for their decays now agree with those measured for lighter nuclei.

The experiment involved Q-value measurements for (^{3}He,t) reactions on a variety of two-component composite targets bombarded by a magnetically analyzed 33.00-MeV beam from the Chalk River MP tandem accelerator. The targets used (and their enrichments) were ^{26}Mg (99.7%), Cd^{34}S (85.6%), ^{42}Ca (93.7%), ^{46}Ti (81.2%), ^{50}Cr (96.8%), and ^{54}Fe (97.4%), each ~ 100 μg/cm^2 thick and evaporated onto the same thickness of ^{27}Al. In

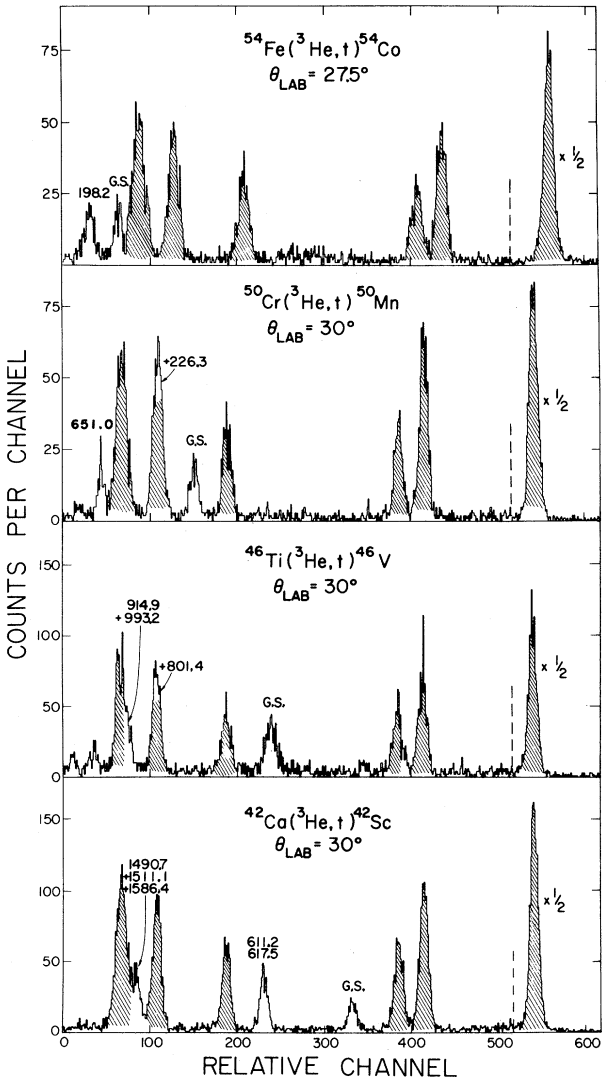

FIG. 1. Sample energy spectra accumulated for a total ^{3}He^{++} charge of ~ 10^4 μC. The shaded peaks are from the reaction ^{27}Al(^{3}He,t)^{27}Si. All others are from the identified reactions; excitation energies are labeled in keV [from Ref. 3 and N. S. P. King *et al.*, Nucl. Phys. A177, 625 (1971)].

addition, targets of $^{42}Ca + ^{26}Mg$ and $^{42}Ca + ^{50}Cr$ were employed. Reaction products were detected in two surface-barrier counter telescopes, each comprising a 1-mm ΔE and a 2-mm E detector. For all target combinations four separate measurements were made in which the telescopes (denoted A and B) and target normal (T) were oriented with respect to the beam as follows[2]: (1) $A = +30°$, $B = -30°$, $T = 0°$; (2) $A = +30°$, $B = -30°$, $T = 180°$; (3) $A = -30°$, $B = +30°$, $T = 180°$; (4) $A = -30°$, $B = +30°$, $T = 0°$. A total of eight spectra were thus accumulated for each target combination. Several examples appear in Fig. 1 where the energy resolution is about 60 keV or better.

Each spectrum was analyzed to yield the energy difference between the ground-state Q values for the two targets involved. The reaction $^{27}Al(^3He, t)^{27}Si$ was common to most measurements and provided an energy scale from the well-known[3] excitation energies of states in ^{27}Si, viz., 0.0, 780.3 ± 0.3, 956.8 ± 0.3, 2163.3 ± 0.6, and 2647.0 ± 0.7 keV. In all cases, the energy scale was linear over the region of interest and yielded an acceptable χ^2 when fitted by the five states of ^{27}Si. The eight measured values of the ground-state Q-value differences for each target combination were averaged together. Although individual values showed the effects of energy loss in the target, the specific choice of relative target and telescope angles ensured that the average was independent not only of target thickness but also of beam-direction variations. Nevertheless, the target thickness was confirmed by measuring the energy loss of 5.5-MeV α particles from ^{241}Am, and the beam direction was controlled by tight collimation (less than $\pm 0.1°$ at the target), which was optically aligned in advance.

The measured Q-value differences are shown in Table I. The quoted errors include the effects of uncertainties both in the peak-centroid determinations (~2 keV) and in the energy of the ^{27}Si states used for calibration (~0.5 keV); in addition there is an allowance (~0.1 to ~1.0 keV from $A = 26$ to $A = 54$) for possible uncertainty in the beam energy. Of the eight Q-value differences tabulated, the last two serve as cross checks on the primary ^{27}Al-based measurements; they agree with the primary data to within 2.1 ± 4.8 and 0.7 ± 4.5 keV, respectively. Previously accepted values are also shown in the table. In determining the latter values, the Q value for the reaction $^{27}Al(^3He, t)^{27}Si$ was taken to be -4828.7 ± 0.9 keV, which is derived from the average of nine[4,5] mutually consistent measurements of the $^{27}Al(p, n)^{27}Si$ threshold energy. The Q values for the reactions $^{26}Mg(^3He, t)^{26}Al$ and $^{34}S(^3He, t)^{34}Cl$ have also been derived from extensive earlier data,[4,6,7] and for these cases there is excellent agreement with our results.

By contrast, the accepted values[4] for the masses of ^{42}Sc, ^{46}V, ^{50}Mn, and ^{54}Co are based solely upon the (p, n) threshold measurements of one group.[8,9] Their results are consistently lower than ours for masses 42, 46, and 54, which may possibly reflect the existence, as discussed in Ref. 9, of undetected compound-nucleus resonances just above the (p, n) threshold, although the discrepancies seem too large to be accounted for by that effect alone. In any event, in estab-

TABLE I. Q-value differences obtained from composite targets.

Reactions		$Q_X - Q_Y$ (keV)	
X	Y	This work	Previous work
$^{26}Mg(^3He, t)^{26}Al$	$^{27}Al(^3He, t)^{27}Si$	808.2 ± 2.0	805.4 ± 1.1 [a,b]
$^{34}S(^3He, t)^{34}Cl$	$^{27}Al(^3He, t)^{27}Si$	-678.7 ± 2.3	-680.3 ± 1.8 [b,c]
$^{42}Ca(^3He, t)^{42}Sc$	$^{27}Al(^3He, t)^{27}Si$	-1611.7 ± 2.6	-1621.1 ± 2.5 [a,b]
$^{46}Ti(^3He, t)^{46}V$	$^{27}Al(^3He, t)^{27}Si$	-2230.8 ± 2.7	-2244.3 ± 2.4 [a,b]
$^{50}Cr(^3He, t)^{50}Mn$	$^{27}Al(^3He, t)^{27}Si$	-2820.0 ± 2.8	-2821.1 ± 2.8 [a,b]
$^{54}Fe(^3He, t)^{54}Co$	$^{27}Al(^3He, t)^{27}Si$	-3432.5 ± 3.0	-3439.8 ± 3.9 [a,b]
$^{42}Ca(^3He, t)^{42}Sc$	$^{26}Mg(^3He, t)^{26}Al$	-2417.8 ± 3.5	-2426.5 ± 2.4 [a]
$^{50}Cr(^3He, t)^{50}Mn$	$^{42}Ca(^3He, t)^{42}Sc$	-1207.6 ± 2.3	-1200.0 ± 3.5 [a]

[a] Ref. 4

[b] The Q value for the reaction $^{27}Al(^3He, t)^{27}Si$ (-4828.7 ± 0.9 keV) was derived from an average of the results from Refs. 4 and 5.

[c] The Q value for the reaction $^{34}S(^3He, t)^{34}Cl$ (-5509.0 ± 1.5 keV) was derived from a recent compilation (Ref. 6) for $A = 34$.

TABLE II. End-point energies and calculated ft values for superallowed decay branches.

Parent nucleus	$E_{\beta max}$ (keV)	$t_{1/2}$ [a] (msec)	ft [b] (sec)	$\mathcal{F}t$ (sec)
^{26m}Al	2982.5±0.5 [c]	6347 ±5	3039±3	3078±3
^{34}Cl	4467.9±1.3 [d]	1530 ±4	3052±9	3084±9
^{42}Sc	5399.9±2.2 [e]	683.9±0.9	3051±7	3093±7
^{46}V	6018.8±2.8 [e]	425.7±0.7	3045±8	3090±8
^{50}Mn	6607.8±2.1 [e]	285.7±0.5	3064±7	3110±7
^{54}Co	7220.5±3.1 [e]	193.4±0.6	3049±11	3092±11

[a] All results taken from Ref. 1 except those for ^{34}Cl which are from Ref. 6.

[b] Partial half-lives include a correction [N. B. Gove and M. J. Martin, Nucl. Data Tables 10, 206 (1971)] for electron capture.

[c] Result from this work averaged with previous results summarized in Ref. 1.

[d] Result from this work averaged with those from Ref. 6.

[e] Result from this work.

lishing the "best" Q values from which to determine the β end-point energies, we have chosen simply to use our own results for those cases with $A>40$, while averaging with previous work[1,6] for masses 26 and 34.

The resultant β-decay energies are listed in Table II. Apart from the data in Table I, they depend only upon the Q value already noted for the reaction ^{27}Al(^{3}He, t)^{27}Si. The best current half-life results[1,6] are also shown, together with calculated ft values for each transition. In terms of the nuclear matrix element and the vector coupling constant, the ft value for a superallowed β decay between $T=1$, $J^\pi=0^+$ states is given by[1]

$$ft(1+\delta_R)=K/G_v'^2|M_v|^2,$$

with

$$G_v'^2=G_v^2(1+\Delta_R),\ |M_v|^2=2(1-\delta_c), \qquad (1)$$

where $K=1.230\,63\times10^{-94}$ cgs units. Here t is the partial half-life for the transition, G_v (G_v') is the (effective) vector coupling constant, M_v is the Fermi matrix element, δ_R (Δ_R) is the outer (inner) radiative correction, and δ_c is the correction to the Fermi matrix element that results from charge-dependent forces. The values of f used in Table II were computed from the decay energies according to the procedure described by Towner and Hardy.[1]

Since the correction terms δ_R and δ_c vary from transition to transition the ft values are not necessarily constant. However the quantity $\mathcal{F}t=ft(1+\delta_R)(1-\delta_c)$ should be independent of the transition involved and should yield directly a value for G_v'. The $\mathcal{F}t$ values listed in Table II incorporate δ_c and δ_R terms taken from Ref. 1. In the case of δ_c, both the Coulomb force and an *ad hoc* charge-dependent nuclear force were considered in evaluating the effect. The radiative correction δ_R to first order in α ($\approx\frac{1}{137}$) is independent of Z, but to higher orders may be expressed[10] as a series of terms of $Z^m\alpha^n$ ($n\geq2$, $m\leq n$); the correction we have actually applied[1,11] is accurate to all orders in terms of the type $Z^m\alpha^{m+1}$. The term of order $Z^2\alpha^2$ is probably negligible[11] but, having never been explicitly evaluated, it must be considered as the only possibly significant term for which any uncertainty remains.

The $\mathcal{F}t$ values from Table II are presented graphically in Fig. 2 together with the three other accurately known[1,6,12] superallowed transitions, viz., the decays of ^{14}O, ^{34}Ar, and ^{38}K^m. The weighted average of all nine values is $\mathcal{F}t=3085.0\pm1.8$ sec, but the corresponding normalized χ^2 is 2.6, which has a probability $<1\%$ of occurring by chance. However, upon removing the ^{50}Mn value the average becomes $\mathcal{F}t=3083.2\pm1.9$ sec with $\chi^2=1.0$ (curve c, Fig. 2). If we accept the possibility of a significant $Z^2\alpha^2$ term in the radiative correction, then the magnitude of that term may be determined by fitting the data with an expression of the form $\mathcal{F}t=(\mathcal{F}t)_0(1+CZ^2\alpha^2)$, where C is a constant. The results, with and without ^{50}Mn (curves a and b), give $C\sim0.2$ and ~0.1 with $\chi^2=1.5$ and 0.8, respectively. The corresponding $(\mathcal{F}t)_0$ values are 3078.7 ± 2.7 and 3080.5 ± 2.8 sec.

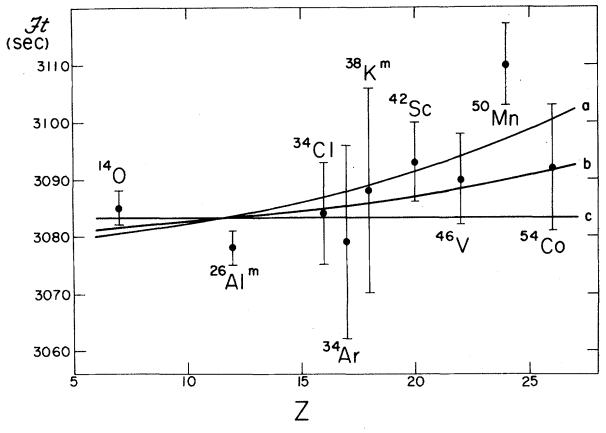

FIG. 2. The corrected experimental $\mathcal{F}t$ values plotted as a function of Z for all cases known to an accuracy better than $\pm 1\%$. The points are labeled by the decay parent. The significance of the curves is explained in the text.

Evidently, with the exception of the ^{50}Mn case, all accurately known $\mathcal{F}t$ values are now concordant. Furthermore, in contrast with a similar analysis of previous data,[13] there is now no positive indication of a $Z^2\alpha^2$ radiative correction term (the coefficient $C \lesssim 0.2$). Finally, after incorporating all apparent uncertainties, including those arising from the various fitting procedures, we recommend $\mathcal{F}t = 3082 \pm 3$ sec as the best current value for nuclear $0^+ \rightarrow 0^+$ β decay. It corresponds to $G_v' = (1.4130 \pm 0.0007) \times 10^{-49}$ erg cm^3. These results now lead to the same conclusion for the inner radiative correction and Cabibbo angle as were derived in Ref. 1, although that earlier work was restricted to nuclei with $A < 40$.

As a concluding remark it should be noted that the half-life of ^{50}Mn rests essentially upon a single measurement[8]; before attaching too much significance to the anomalous nature of the ^{50}Mn decay, a re-examination of its half-life is indicated.

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