SUPERALLOWED $0^+ \rightarrow 0^+$ NUCLEAR $\beta$-DECAYS 
AND CABIBBO UNIVERSALITY

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Abstract: Recent experimental data have significantly improved the overall consistency of $f_t$ values for superallowed $0^+ \rightarrow 0^+$ nuclear $\beta$-decays. All relevant data are collated in this paper and theoretical electromagnetic corrections applied. The resulting corrected $f_t$ values are constant to within two parts in 3000. This constitutes an exacting experimental confirmation of the CVC hypothesis. Statistical tests applied to the data gave no positive indication of any inadequacies in the theoretical corrections. These tests also set a new limit for the Fierz interference constant, $b_F \leq 0.006$, which is an order of magnitude smaller than previous determinations. The value of the vector coupling constant of nuclear $\beta$-decay, established from these data, is compared with muon and hyperon $\beta$-decays as a test of Cabibbo universality. It is shown that universality is achieved under specific conditions on the mass of the neutral vector boson.

1. Introduction

The last survey of experimental $f_t$ values for $T = 1, 0^+ \rightarrow 0^+$ superallowed $\beta$-decays \cite{1} was completed in October 1972. At that time, fifteen transitions had been studied and the $f_t$ values for eight of them were apparently established with an uncertainty of less than $\pm 1\%$. Yet there remained some puzzling discrepancies. According to the conserved vector current (CVC) hypothesis all such $f_t$ values should be identical providing that small electromagnetic corrections are accounted for. In fact, though, a least-squares analysis of the fifteen data points yielded an average value with a $\chi^2$ per degree of freedom of 5.0, which is high enough to indicate serious disagreement between theory and experiment.

The data appeared to divide into two groups according to the mass of the nuclei involved. The $f_t$ values for the heavier nuclei, $A \geq 38$, were consistently $1\%$ higher than those for the lighter nuclei. If this trend had been borne out by further experiments, it could have signalled an inadequacy in the calculated electromagnetic corrections since such corrections might reasonably be expected to increase with increasing nuclear charge. Consequently, in 1972 it was difficult to extract a "best" $f_t$ value from the data, and as a result the implications for weak interaction theories, which hinged on this "best" value, were clouded with some uncertainty.

Since 1972 there has been fresh experimental work that has removed this difficulty. Now, of the fifteen data points, ten have quoted uncertainties of less than $1\%$ and all are concordant with one another. It seems timely, therefore, to reassess the experimental data and their implications.
The connection between the half-life, the nuclear matrix element and the vector coupling constant for superallowed $\beta$-decay between $T = 1, J^\pi = 0^+$ states is given by

$$\tau(1 + \delta_R) = \frac{K}{G_V^2 |M_V|^2},$$

(1)

with

$$G_V^2 = G_V(1 + \Delta_R),$$

$$|M_V|^2 = 2(1 - \delta_C),$$

$$K = \frac{2\pi^3 \ln 2 \hbar^2 c^6}{(mc^2)^5} = (1.23062 \pm 0.00003) \times 10^{-94} \text{ erg}^2 \cdot \text{cm}^6 \cdot \text{sec},$$

where the physical constants used to evaluate $K$ were taken from ref. 2). Here $f$ is the statistical rate function, $\tau$ is the partial half-life for the transition, $G_V$ is the effective vector coupling constant, and $M_V$ is the Fermi matrix element. Radiative corrections have been expressed as a sum of two terms 3), $\delta_R$ which varies from nucleus to nucleus and $\Delta_R$ which is a constant. A further correction, $\delta_C$, modifies the Fermi matrix element as a result of Coulomb and nuclear charge-dependent forces. It is necessary to calculate values for all correction terms $\delta_R$, $\Delta_R$ and $\delta_C$ before the vector coupling constant $G_V$ can be determined from an experimental $\tau$ value.

The statement of CVC, in this context, is that $G_V$ suffers no renormalisation and is indeed constant from nucleus to nucleus. In practice a test of this statement requires the determination of a corrected $\tau$ value, $\bar{\tau}$:

$$\bar{\tau} = \tau(1 + \delta_R)(1 - \delta_C),$$

(2)

which can then be related simply to $G_V$ via

$$\bar{\tau} = \frac{K}{2G_V^2(1 + \Delta_R)}.$$  

(3)

Since the quantities on the r.h.s. of this equation are believed to be nucleus independent, the assertion is that the corrected $\bar{\tau}$ value should be constant for all superallowed $T = 1$ nuclear transitions.

Our procedure will be to examine all relevant experimental data on the fifteen known transitions and from them determine a set of $\tau$ values to which the calculated corrections $\delta_R$ and $\delta_C$ will be applied. The resulting $\bar{\tau}$ values are seen to be consistent with one another and a "best" average will be extracted. Before trusting the result, however, we shall additionally test its dependence on the details of the calculated corrections, the uncertainties of which are first examined in sect. 2. Finally, the "best" $\bar{\tau}$ value will be used in conjunction with data on the weak decays of hyperons and mesons to examine the universality of weak interaction processes.
2. Theoretical uncertainties

2.1. RADIATIVE CORRECTIONS

Radiative corrections arise from the interaction of the decaying nucleon and the emitted positron with the external electromagnetic field. They may be expressed as a perturbation series in $Z \alpha$, all terms $Z^m \alpha^n$ with $m \leq n$ being present. The largest corrections of this type are actually incorporated in the statistical rate function $f$ and in the correction $\delta_C$, but many remain to be included in $\delta_k$ and $\Delta_k$. To clarify the nature of these corrections and how they are accounted for in the analysis we refer to the diagrams in fig. 1.

In the absence of electromagnetic interactions, the $\beta$-decay process is represented by diagram (a) with all four particles – proton, neutron, positron and neutrino – being described by plane waves. Succeeding diagrams describe modifications caused by the electromagnetic interactions. Diagrams (b) and (b') are corrections in which

Fig. 1. Feynman diagram for positron decay $p \rightarrow n + e^+ + \nu_e$ in the intermediate vector boson model, diagram (a). Diagrams (b) through to (e) are for selected radiative corrections as discussed in the text.
the positron interacts with the static Coulomb field of the daughter nucleus. These
effects, of order $Z^x$ and $Z^2x^2$ respectively, plus other higher order terms of the same
$Z^x$ type, are included in the calculation of $f$ through the use of a positron wave
function that is obtained by exactly solving (numerically) the Dirac equation for a
positron in the appropriate Coulomb field.

Diagrams (c) and (c') show similar corrections for the interaction of the decaying
nucleons with the static Coulomb field. They are usually considered part of the
nuclear structure calculation and constitute the term $\delta_C$, which will be discussed in
subsect. 2.2. In fact, because of the nature of the Fermi interaction, the contribution
of diagram (c) is zero with the result that $Z^2x^2$ is the leading order term in $\delta_C$.

The order-$\alpha$ correction in diagram (d) contributes the major component of what
are conventionally referred to as the radiative corrections, viz. $\delta_R$ and $\Delta_R$. It has been
extensively studied in the literature 3, 4, 5). The most recent calculation is a quark-
model approach by Sirlin 5), in which the exchange of both a $Z$ vector boson and
a photon [diagram (d)] between the hadron and the positron is considered. In
evaluating the sum of the two effects, only the difference between the radiative
corrections for muon and nuclear $\beta$-decay need actually be calculated, since ulti-
mately these two decays are compared as a test of universality. The result for the
radiative correction to order $\alpha$, viz. $R^\alpha$, is

$$R^\alpha = \alpha \left[ <g(W, W_0)> + 3 \ln \left( \frac{M_Z}{M_P} \right) + 3\rho \ln \left( \frac{M_Z}{M_\Lambda} \right) \right],$$

(4)

where $g(W, W_0)$ is a single universal function derived earlier by Sirlin 5) and num-
merically evaluated by Wilkinson and Macefield 7). This function is averaged over
all electron energies $W$ and depends only on $W_0$ the maximum energy.

Surprisingly this quark-model approach yields the same expression (to a good
approximation) as had earlier models providing the parameter $M_Z$ is interpreted
appropriately. Here, where both photon and neutral current contributions are
included, $M_Z$ is the mass of the $Z$ vector boson. In the local V-A theory, $M_Z$ is inter-
preted as the mass cut-off, while in an earlier intermediate vector boson theory 6),
$M_Z$ becomes the mass of the $W$ vector boson.

The third term in eq. (4) arises from the axial-vector current \dagger and is model de-
pendent \S). The parameter $\rho$ depends on the nature of the quark model, \$[\rho = 1$ for
four quarks with integer charges \$) and $\rho = \frac{1}{3}$ for three coloured quartets], and $M_\Lambda$
is the mass of the exchanged axial vector meson [usually taken to be the $A_1$ meson,
with \$) $M_\Lambda \approx 1100$ MeV].

There are many other diagrams of order $\alpha$ that can contribute to the radiative
correction. These have not been included either because they make the identical
correction to muon decay (e.g. photon exchange between the intermediate vector
boson and the positron) or because their contribution is negligible [e.g. the inter-

\S The axial-vector current does not of course contribute to the "bare" Fermi decay, diagram (a), but can
contribute when a photon line is introduced.
mediate vector boson interacting with the static Coulomb field gives a contribution of order \( Z \alpha (M_\nu/M_w)^2 \).

Turning now to higher orders, the largest contribution of order \( Z \alpha^2 \) is illustrated in diagram (e). It has been evaluated by Jaus and Rasche\(^8\) in a local V-A theory, but since the integrals in this case are convergent, with no cut-offs being required, intermediate vector boson theories (at least to lowest order in the boson mass) would lead to essentially the same result. Similar diagrams of order \( Z^2 \alpha^3 \) have also been evaluated by Jaus\(^9\).

Combining the radiative corrections of order \( \alpha, Z \alpha^2 \) and \( Z^2 \alpha^3 \), we write

\[
\delta_R = \delta_R^\alpha + \delta_R^{Z \alpha^2} + \delta_R^{Z^2 \alpha^3},
\]

where

\[
\delta_R^\alpha = \frac{\alpha}{2\pi} \langle g(W, W_0) \rangle,
\]

\[
\delta_R^{Z \alpha^2} = Z \alpha^2 \ln \left( \frac{M_\nu}{m_e} \right) + \cdots,
\]

\[
\delta_R^{Z^2 \alpha^3} \approx \frac{Z^2 \alpha^3}{\pi} (3 \ln 2 - \frac{3}{2} + \frac{1}{2} \pi^2) \ln \left( \frac{M_\nu}{m_e} \right)
\]

and

\[
\delta_R = \frac{\alpha}{2\pi} \left[ 3 \ln \left( \frac{M_Z}{M_\nu} \right) + 3 \rho \ln \left( \frac{M_Z}{M_\Lambda} \right) \right].
\]

The corrections of order \( \alpha \) have been arbitrarily separated into \( \delta_R^\alpha \) and \( \delta_R \), so that all the nucleus-dependent terms can be grouped together in \( \delta_R \).

Although the largest corrections of order \( Z \alpha^2 \) and \( Z^2 \alpha^3 \) are included, diagrams of these orders in which a photon interacts with the hadron or the intermediate boson have never been explicitly calculated. Consequently the first omission in the calculated radiative correction might possibly appear at order \( Z \alpha^2 \) and the experimental data will be examined in sect. 5 for evidence of any residual \( Z \)-dependence indicative of such a problem.

2.2. THE CORRECTION \( \delta_C \)

For superallowed \( \beta \)-decays the parent and daughter nuclei are members of a common isotopic spin multiplet and in the absence of any Coulomb or charge-dependent nuclear effects their wave functions will be identical. In practice, the Coulomb force destroys the isospin purity of the nuclear states and modifies the nuclear matrix element. This modification is parametrised by the correction \( 1 - \delta_C \). Expressions for \( \delta_C \) have been derived by Blin-Stoyle\(^10\) and by Towner and Hardy\(^1\) who show that the correction depends upon the square of a Coulomb matrix element; that is, the correction is of order \( Z^2 \alpha^2 \).
We identify two contributions to $\delta_c$. First, the tail of the radial wave function for protons extends further than that for neutrons, so the radial overlap of the parent and daughter nuclei is reduced from the normally assumed value of unity. Second, the degree of configuration mixing can vary across the multiplet, and this too gives a reduction in the nuclear matrix element. These two contributions have been calculated by Towner and Hardy. The first makes between 0.25 and 0.75% correction to the $f_t$ value and can be considered reasonably well established, while the second contributes between 0.1 and 0.3% but is much less certain. The latter is strongly nuclear-model dependent, being a sensitive function of the precise details of the shell-model calculation actually used. In sect. 5, the ability of the model to reproduce nucleus-to-nucleus variations in $\delta_c$ will be tested by analysing the data both with and without this calculated correction.

3. Experimental data

The $f_t$ value of a particular $\beta$-transition depends upon the transition energy $Q_{ee}$ and its partial half-life, $t$. Where several transitions from the parent state are possible, both the half-life of the state and the branching ratio for the transition of interest must be measured to determine $t$. In principle, then, for the superallowed transitions of interest here, three quantities must be known: the half-life of the $\beta$-emitter, the decay energy of the $0^+ \rightarrow 0^+$ transition, and its branching ratio. The relevant experimental data are surveyed in tables 1-4.

In our treatment of the data we have considered all measurements formally published before August 1975 whose quoted uncertainties are within a factor of ten of the most precise measurement for each quantity. All appear in the tables with the exception of a few references for which there was evidence of significant and systematic errors. These have been noted in footnotes to the tables.

The $Q_{ee}$ data have been separated into two groups depending on whether the energy can be measured directly by a nuclear reaction (table 2) or must be taken from the difference of two nuclear masses, each independently determined (table 3). For the former group all measurements were expressed as a $Q_{ee}$ value, which $(p, n)$ and $(^3\text{He}, t)$ reactions measure directly but which in other cases requires knowledge of an additional nuclear mass. In all such cases the necessary masses were of precisely known stable nuclei and the 1971 Mass Tables (table 1 ref. Wa71) were used. For the second group, both parent and daughter nuclei are unstable so we have listed in table 3 the measured mass excesses for each. Many are common to Wa 71 but suitable revisions and additions have been made to update the results. The final $Q_{ee}$ values, derived from the average mass excesses, are also listed in the last column of the table.

The branching ratios for the superallowed branches from $T_z = -1$ nuclei are given in table 4. The corresponding decays from $T_z = 0$ nuclei lead to doubly even nuclei in which the $0^+$ ground state is the only available level that can be populated by allowed $\beta$-decay. The $0^+ \rightarrow 0^+$ branch is then assumed to account for 100% of
<table>
<thead>
<tr>
<th>Decaying nucleus</th>
<th>Measured half-lives, $t_1$ (ms) a)</th>
<th>Average, all values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

$T_{ni} = -1$:

<table>
<thead>
<tr>
<th>Decaying nucleus</th>
<th>$t_1$ (ms)</th>
<th>scale</th>
<th>conf. level (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{10}$C</td>
<td>19480 ± 50 (Ea62)</td>
<td>19270 ± 80 (Ba63)</td>
<td>19280 ± 20 (Az74)</td>
</tr>
<tr>
<td>$^{14}$O</td>
<td>70910 ± 180 (He61)</td>
<td>71000 ± 180 (Ba62a)</td>
<td>71300 ± 180 (Fr63)</td>
</tr>
<tr>
<td>$^{18}$Ne</td>
<td>1460 ± 70 (Bu61a)</td>
<td>1670 ± 20 (Al70)</td>
<td>1690 ± 40 (As70)</td>
</tr>
<tr>
<td>$^{22}$Mg</td>
<td>4030 ± 50 (Ga67)</td>
<td>3970 ± 90 (Be72)</td>
<td>3857 ± 9 (Ha75)</td>
</tr>
<tr>
<td>$^{26}$Si</td>
<td>2100 ± 100 (Fr63)</td>
<td>2210 ± 21 (Ha75)</td>
<td>2205 ± 22</td>
</tr>
<tr>
<td>$^{30}$S</td>
<td>1180 ± 40 (Ba67)</td>
<td>1220 ± 30 (Mo71)</td>
<td>1181 ± 13 (Sc74)</td>
</tr>
<tr>
<td>$^{34}$Ar</td>
<td>844.5 ± 3.4 (Ha74d)</td>
<td>844.5 ± 3.4 (Ha74d)</td>
<td>844.5 ± 3.4 (Ha74d)</td>
</tr>
<tr>
<td>$^{38}$Ca</td>
<td>470 ± 20 (Ka68)</td>
<td>439 ± 12 (Ga69)</td>
<td>450 ± 70 (Zi72)</td>
</tr>
<tr>
<td>$^{42}$Ti</td>
<td>173 ± 14 (Al69)</td>
<td>202 ± 5 (Ga69)</td>
<td>200 ± 20 (Ni69)</td>
</tr>
</tbody>
</table>

$T_{ni} = 0$:

<table>
<thead>
<tr>
<th>Decaying nucleus</th>
<th>$t_1$ (ms)</th>
<th>scale</th>
<th>conf. level (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{26m}$Al</td>
<td>6390 ± 20 (Ja60)</td>
<td>6346 ± 5 (Fr69b)</td>
<td>6351 ± 10 (Ha72a)</td>
</tr>
<tr>
<td>$^{34}$Cl</td>
<td>1580 ± 10 (Ja60)</td>
<td>1560 ± 14 (Ja61)</td>
<td>1534 ± 3 (Ha72a)</td>
</tr>
<tr>
<td>$^{38m}$K</td>
<td>951 ± 7 (C157a)</td>
<td>938 ± 8 (Ja60)</td>
<td>944 ± 12 (Li60)</td>
</tr>
<tr>
<td>$^{42}$Sc</td>
<td>680 ± 10 (C157b)</td>
<td>695 ± 7 (Ja60)</td>
<td>650 ± 10 (Ne65)</td>
</tr>
<tr>
<td>$^{46}$V</td>
<td>425.3 ± 2.0 (Al73)</td>
<td>423.4 ± 2.0 (Ha74c)</td>
<td>283.36 ± 0.5 (Ho74)</td>
</tr>
<tr>
<td>$^{50}$Mn</td>
<td>285.1 ± 0.9 (Al73)</td>
<td>284.0 ± 0.4 (Ha74c)</td>
<td>282.8 ± 0.3 (Fr75)</td>
</tr>
<tr>
<td>$^{54}$Co</td>
<td>193.1 ± 0.8 (Al73)</td>
<td>193.4 ± 0.4 (Ha74c)</td>
<td>193.0 ± 0.3 (Ho74)</td>
</tr>
</tbody>
</table>

*) Consideration has been given to all published measurements whose quoted uncertainties are within a factor of ten of the most precise measurement. Of these, the following references (and nuclei to which they were applicable) have been rejected: Mi58(26mAl, 34Cl and 38mK), Fr62(26mAl), Fr65a(42Sc, 46V and 50Mn) and Fr65b(54Co). The first of these, Mi58, reported with little documentation on seven half-lives in all, of which most disagree significantly with subsequent work. The remaining references were from the Harwell group before the systematic bias in their half-life analysis had been identified (Fr69b).

b) The uncertainties originally quoted on these measurements appear unduly optimistic in the light of difficulties (e.g. see Fr69b) more recently ascertained; we have arbitrarily increased their uncertainties to ±0.25%.

c) This reference replaces C171.

d) This reference replaces Ha72b.

e) This reference replaces Fr66b.

f) This reference replaces Fr65b.

g) Only relative branching ratios were used from this reference.
References to table 1.

Aj72 F. Ajzenberg-Selove, Nucl. Phys. A190 (1972) 1
Al73 D. E. Alburger, Phys. Rev. C7 (1973) 140
An70 A. Antilla, M. Bister and E. Arminen, Z. Phys. 234 (1970) 455
Ba63 F. J. Bartels, Phys. Rev. 132 (1963) 1673
Ba64 R. O. Bondedal and D. H. Wilkinson, Phys. Lett. 32B (1964) 229
Be68 R. K. Bardin, C. A. Barnes, W. A. Fowler and P. A. Seeger, Phys. Soc. Sec. 69
B678 R. K. Bardin, C. A. Barnes, W. A. Fowler and P. A. Seeger, Phys. Soc. Sec. 69
### TABLE 2
Decay energy for superallowed $\beta$-branches leading to stable nuclei

<table>
<thead>
<tr>
<th>Decaying nucleus</th>
<th>Measured decay energy $Q_{\text{en}}$ (keV)*</th>
<th>Average value</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$Q_{\text{en}}$ (keV)</td>
<td>scale</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>$T_z = -1$:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{10}$C</td>
<td>1910.9 ± 1.8 b) (Fr66a)</td>
<td>1910.1 ± 0.6 b) (Ro74)</td>
<td>1910.22 ± 0.59</td>
</tr>
<tr>
<td>$^{14}$O</td>
<td>2831.1 ± 0.8 d) (Bu61b)</td>
<td>2829.9 ± 1.3 d) (To61a)</td>
<td>2831.83 ± 0.36</td>
</tr>
<tr>
<td></td>
<td>2832.0 ± 0.6 d) (Ba62a)</td>
<td>2832.3 ± 0.6 d) (Ro70)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2835.4 ± 2.8 d) (Ku65)</td>
<td>2832.2 ± 1.5 d) (Fr68, Cl73)</td>
<td></td>
</tr>
<tr>
<td>$T_z = 0$:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{26m}$Al</td>
<td>4231.6 ± 1.4 (Fr62)</td>
<td>4233.0 ± 4.2 f) (Sp64)</td>
<td>4232.64 ± 0.49</td>
</tr>
<tr>
<td></td>
<td>4231.6 ± 1.6 (Fr69b, Cl73)</td>
<td>4233.1 ± 0.6 (De69)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4230.3 ± 2.2 (Ha74b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{34}$Cl</td>
<td>5492.1 ± 2.4 (Gr69)</td>
<td>5489.4 ± 1.9 (Ry73) b)</td>
<td>5490.0 ± 1.3</td>
</tr>
<tr>
<td></td>
<td>5488.7 ± 2.5 (Ha74b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{38m}$K</td>
<td>6056.0 ± 10.2 i) (Sp64)</td>
<td>6048.9 ± 15.1 i) (Bl66)</td>
<td>6046.3 ± 3.2</td>
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<td>6040.4 ± 15.1 i) (Ta63)</td>
<td>6063.9 ± 10.2 i) (Fe72)</td>
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<td></td>
<td>6043.2 ± 3.4 (Sq75)</td>
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</tr>
<tr>
<td>$^{42}$Sc</td>
<td>6421.9 ± 2.2 (Ha74b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{46}$V</td>
<td>7059.8 ± 9.0 (Ja63)</td>
<td>7040.8 ± 2.8 (Ha74b)</td>
<td>7042.5 ± 5.4</td>
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<tr>
<td>$^{50}$Mn</td>
<td>7629.8 ± 2.1 (Ha74b)</td>
<td>7629.8 ± 2.1</td>
<td>1.0</td>
</tr>
<tr>
<td>$^{54}$Co</td>
<td>8242.5 ± 3.1 (Ha74b)</td>
<td>8240.5 ± 1.8 (Ho74) a)</td>
<td>8241.0 ± 1.6</td>
</tr>
</tbody>
</table>

For the references, see table 1.

* Consideration has been given to all published measurements whose quoted uncertainties are within a factor of ten of the most precise measurement. Of these, Fr65a ($^{42}$Sc, $^{46}$V and $^{50}$Mn) has been rejected since its results all disagree significantly with subsequent work. $Q_{\text{en}}$ values refer to the superallowed $0^+ \to 0^+$ decay branch. Where necessary, stable nuclei masses were taken from Wa71 (see text).

b) Values derived from ground-state $Q$-values using 1740.16 ± 0.17 keV (Fr69a) as the excitation energy of the lowest $0^+(T = 1)$ state in $^{10}$B.

c) The value attributed to this reference appears as corrected by Ro74.

d) Values derived from ground-state $Q$-values using 2312.81 ± 0.06 keV (Aj70) as the excitation energy of the lowest $0^+(T = 1)$ state in $^{14}$N.

e) The values attributed to these references appear as corrected by Ry65.

f) This value derived from ground-state $Q$-value using 228.44 ± 0.15 keV (De69) as the excitation energy of the lowest $0^+(T = 1)$ state in $^{26}$Al.

g) This reference replaces Mu67.

h) This reference replaces Fr64, Fr65c and Mu67.

i) These values derived from ground-state $Q$-values using 131.0 ± 2.0 keV (En73) as the excitation energy of the lowest $0^+(T = 1)$ state in $^{38}$K.
TABLE 3
Decay energy for superallowed β-branches leading to unstable nuclei

<table>
<thead>
<tr>
<th>Decaying nucleus</th>
<th>Daughter nucleus</th>
<th>Measured mass excess (keV)</th>
<th>Average mass excess</th>
<th>$Q_{\alpha}\text{(^a)}$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>$^{18}$Ne</td>
<td></td>
<td>5321.4 ± 6.0 (To61b)</td>
<td>5328.4 ± 13.0 (Du61)</td>
<td>5310.9 ± 9.2 (Fr63)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>886.0 ± 4.0 (Ro50)</td>
<td>872.18 ± 0.79 (Bo64)</td>
<td>875.2 ± 2.8 (Pr67)</td>
</tr>
<tr>
<td>$^{22}$Mg</td>
<td></td>
<td>-391 ± 11 (Mc70)</td>
<td>-389 ± 21 (Ad71)</td>
<td>-412 ± 10 (Pa72)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-399 ± 3 (Ha74a)</td>
<td>-394 ± 2 (No74)</td>
<td>-5183.5 ± 2.1 (Da58)</td>
</tr>
<tr>
<td>$^{22}$Na</td>
<td></td>
<td>-5186.5 ± 5.0 (Ma50)</td>
<td>-5188.5 ± 5.0 (Wr53)</td>
<td>-5182.8 ± 0.7 (Be68)</td>
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<tr>
<td></td>
<td></td>
<td>-5185.5 ± 3.0 (Ha58)</td>
<td>-5184.6 ± 1.6 (We68)</td>
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<tr>
<td>$^{26}$Si</td>
<td></td>
<td>-7130 ± 13 (Fr63)</td>
<td>-7146 ± 30 (Mc67)</td>
<td>-7156 ± 18 (Mi67)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-7136 ± 30 (Ha68)</td>
<td>-7166 ± 15 (Ad68)</td>
<td>-7143 ± 3 (Ha74a)</td>
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<tr>
<td>$^{26m}$Al</td>
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<td>-14088 ± 17 (Fr63)</td>
<td>-14052 ± 25 (Mc67)</td>
<td>-14058 ± 15 (Mi67)</td>
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<tr>
<td></td>
<td></td>
<td>-14066 ± 30 (Ha68)</td>
<td>-14081 ± 12 (Pa72)</td>
<td>-14062 ± 3 (Ha74a)</td>
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<tr>
<td>$^{30}$S</td>
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<td>-20200 ± 12 (Ba62b)</td>
<td>-20195 ± 10 (Sp64)</td>
<td>-20201 ± 3 (Ha67)</td>
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<td></td>
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<td>-20203 ± 5 (Mu67)</td>
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<tr>
<td>$^{30}$P</td>
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<td>-18394 ± 30 (Mc67)</td>
<td>-18395 ± 15 (Mi67)</td>
<td>-18394 ± 30 (Ha68)</td>
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<tr>
<td>$^{34}$Ar</td>
<td></td>
<td>-18370 ± 11 (Pa72)</td>
<td>-18379 ± 3 (Ha74a)</td>
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<tr>
<td>$^{34}$Cl</td>
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<td>-24437.1 ± 2.1 (Gr69)</td>
<td>-24439.8 ± 2.5 (Ry73)</td>
<td>-24440.5 ± 3.0 (Ha74b)</td>
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<tr>
<td>$^{38}$Ca</td>
<td></td>
<td>-22048 ± 25 (Ha66)</td>
<td>-22005 ± 21 (Sh69)</td>
<td>-22079 ± 11 (Pa72)</td>
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<td></td>
<td></td>
<td>-22080 ± 30 (Zi72)</td>
<td></td>
<td></td>
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<tr>
<td>$^{38m}$K</td>
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<td>-28658 ± 10* (Sp64)</td>
<td>-28666 ± 15* (Bl66)</td>
<td>-28670 ± 15* (Ta63)</td>
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<td></td>
<td>-28651 ± 10* (Fe72)</td>
<td>-28670.5 ± 2.9 (Sb75)</td>
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<tr>
<td>$^{42}$Ti</td>
<td></td>
<td>-25120.7 ± 6.1 (Mi67)</td>
<td>-25086 ± 30 (Ha68)</td>
<td>-25115 ± 20 (Zi72)</td>
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<tr>
<td>$^{42}$Sc</td>
<td></td>
<td>32116.2 ± 3.1* (Be68)</td>
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</tbody>
</table>

For the references see table 1.

* The $Q_{\alpha}$ values listed correspond to the $0^+ \rightarrow 0^+$ superallowed transition between the indicated nuclei.

b) The value attributed to this reference appears as corrected by Ry65.

c) This value derived from ground-state $Q$-value using 1041.7 ± 0.6 keV (Aj72, Ha75) as the excitation energy of the lowest $0^+(T = 1)$ state in $^{18}$F.

d) This value derived from ground-state $Q$-value using 657.00 ± 0.14 keV (En73) as the excitation energy of the lowest $0^+(T = 1)$ state in $^{18}$F.

e) These values were derived directly from results in table 2.

f) This value derived from ground-state $Q$-value using 677.2 ± 0.4 keV (En73) as the excitation energy of the lowest $0^+(T = 1)$ state in $^{18}$F.

* These values derived from the ground-state mass excess using 131.0 ± 2.0 keV (En73) as the excitation energy of the $0^+(T = 1)$ isomer in $^{38m}$K.
Decaying nucleus | Branching ratio (%) | Remarks
--- | --- | ---
\( ^{10}\text{C} \) | 1.465 ± 0.014 (Ro72) | reference replaces Fr69a
\( ^{14}\text{O} \) | 99.328 ± 0.012 (C71, Si66, Ka69) | value is an average of 3 measurements (Ba67, Ga67, Ha75); confidence level = 73%
\( ^{18}\text{Ne} \) | 7.66 ± 0.21 (Ha75) | an earlier result of (63 ± 3)% (Fr63, but see also Mo71) is evidently erroneous.
\( ^{22}\text{Mg} \) | 54.0 ± 1.1 | reference replaces Fr69a
\( ^{26}\text{Si} \) | 74.9 ± 0.9 (Ha75) | value is an average of 3 measurements (Ba67, Ga67, Ha75); confidence level = 73%
\( ^{30}\text{S} \) | 77.5 ± 1.0 (Fr63, Mo71) | an earlier result of (63 ± 3)% (Fr63, but see also Mo71) is evidently erroneous.
\( ^{34}\text{Ar} \) | 94.44 ± 0.23 (Ha74d) |
\( ^{42}\text{Ti} \) | 44 ± 14 (Ga69, Al69) |

For the references see table 1.

*) The branching ratios for all superallowed transitions from \( T_z = 0 \) nuclei are 100% (Li73).

The statistical procedure followed in analyzing the tabulated data were those used by the Particle Data Group in their periodic reviews of particle properties [e.g. ref. 2)]. Weighted averages were calculated according to:

\[
\bar{x} \pm \delta \bar{x} = \frac{\sum w_i x_i}{\sum w_i} \pm \left( \frac{\sum w_i}{\sum w_i} \right)^{\frac{1}{2}},
\]

where the sums extend over all \( N \) relevant measurements. In each case, \( \chi^2 \) was calculated and a scale factor \( S \) determined:

\[
S = \left[ \frac{\chi^2}{(N-1)} \right]^{\frac{1}{2}}.
\]

If \( S > 1 \) and the \( \delta x_i \) are all about the same size, then we increase the error \( \delta \bar{x} \) in eq. (7) by the factor \( S \), which is equivalent to assuming that all the experimental errors were underestimated by the same scale factor. If \( S > 1 \), but the \( \delta x_i \) are of widely varying magnitudes, \( S \) was recalculated using only those results for which \( \delta x_i \leq 3N^{\frac{1}{2}} \delta \bar{x} \); the scale factor was then applied in the same way.

Uncertainties on the averages listed in tables 1–4 have been scaled according to this prescription. However, the corresponding scale factors are also tabulated so that the reader can recover the unscaled error easily; of course, the average value itself is always unchanged. In each case, the confidence level (CL), i.e. the probability of obtaining a higher \( \chi^2 \) than the observed value 2), is also given.

As a guide to the consistency of the data, several ideograms 2) are plotted in fig. 2. An ideogram is the sum of \( N \) Gaussians; each Gaussian represents one measurement, its centroid being at the measured value \( x_i \), its width \( \pm \delta x_i \) and its area = \( 1/\delta x_i \). The individual measurements with their error bars are also plotted, together with a
vertical line (and horizontal scaled uncertainty) at the value of the weighted average. The reason for weighting individual measurements by \(1/\delta x_i\) in the ideogram rather than \((1/\delta x_i)^2\) as in eq. (7) is to give greater emphasis to systematic effects. Use of the latter weighting is equivalent to assuming that large systematic errors are as unlikely as large statistical fluctuations. Comparison of the ideogram with the weighted average and scaled uncertainty gives a visual impression of the systematic reliability of the result.

4. The \(\mathcal{T}\) values

The statistical rate function \(f\) is defined by

\[
f = \int_{1}^{W_0} pW(W_0 - W)^2F(Z, W)C(W) \, dW,
\]

where \(W_0\) is the maximum \(\beta\)-energy in electron rest mass units, \(W\) the electron energy and \(p\) the electron momentum (\(p^2 = W^2 - 1\) in these units). The quantity

\[
\text{\textdagger}\quad \text{The energy } W_0 \text{ relates to } Q_{ec} \text{ listed in tables 2 and 3 via } W_0 = Q_{ec}/mc^2 - 1.
\]
<table>
<thead>
<tr>
<th>表 5</th>
<th>超允许分支的衍生结果</th>
</tr>
</thead>
<tbody>
<tr>
<td>衰变电子部分寿命 $t$ (ms)</td>
<td>$\delta_c$ (%)</td>
</tr>
<tr>
<td>核 $^{13}$C</td>
<td>$1318000 \pm 13000$</td>
</tr>
<tr>
<td>$^{14}$O</td>
<td>$71414 \pm 59$</td>
</tr>
<tr>
<td>$^{15}$Ne</td>
<td>$21980 \pm 60$</td>
</tr>
<tr>
<td>$^{22}$Mg</td>
<td>$7160 \pm 150$</td>
</tr>
<tr>
<td>$^{26}$Si</td>
<td>$10523 \pm 46$</td>
</tr>
<tr>
<td>$^{28}$S</td>
<td>$1968.8 \pm 4.2$</td>
</tr>
<tr>
<td>$^{34}$Ar</td>
<td>$19954.9 \pm 9.8$</td>
</tr>
<tr>
<td>$^{38}$Ca</td>
<td>$3423 \pm 9.8$</td>
</tr>
<tr>
<td>$^{42}$Ti</td>
<td>$7023 \pm 9.8$</td>
</tr>
<tr>
<td>$^{42}$Sc</td>
<td>$7023 \pm 9.8$</td>
</tr>
<tr>
<td>$^{46}$V</td>
<td>$5300 \pm 9.8$</td>
</tr>
<tr>
<td>$^{50}$Mn</td>
<td>$3079 \pm 9.8$</td>
</tr>
</tbody>
</table>

| $T_{1/2}$ | 1 | 0 |
|---|---|
| $^{26}$Al | $472.19 \pm 0.33$ | 0.084 | 0.0063 |
| $^{24}$Mg | $1992.8 \pm 2.7$ | 0.081 | 0.0063 |
| $^{26}$Si | $13084.1 \pm 9.8$ | 0.083 | 0.0063 |
| $^{34}$Ar | $4455.4 \pm 8.5$ | 0.098 | 0.0063 |
| $^{38}$Ca | $7154 \pm 9.8$ | 0.072 | 0.0063 |
| $^{42}$Ti | $10714 \pm 9.8$ | 0.086 | 0.0063 |

1) Derived from ref. (13).
2) Defined in eq. (21).

---

*J. C. Hardy and I. S. Towner*
$F(Z, W)$ is known as the Fermi function and $C(W)$ the shape correction factor\textsuperscript{11).}

The latter has a value close to unity for most values of $W$ and its departure from unity reflects the influence of screening by the atomic electrons, the dependence of the nuclear matrix elements on $W$, and the presence of second-forbidden matrix elements. The details of the evaluation of the product $F(Z, W)C(W)$, which depends on the solutions of the Dirac equation for the electron, are to be found in ref.\textsuperscript{1).} With the techniques discussed there, we have re-evaluated the statistical rate function $f$ for all transitions using the decay energies listed in tables 2 and 3. In addition, a small kinematic recoil correction\textsuperscript{12)} has been incorporated. The results appear in column 1 of table 5.

The partial half-lives $t$ are obtained from the total nuclear half-lives $t_{\pm}$ (see table 1) according to the formula

$$t = \frac{t_{\pm}}{\text{BR}} 100 (1 + \frac{1}{100} \text{EC}),$$  \hspace{1cm} (10)
where \( BR \) is the branching ratio (see table 4) and \( EC \) the calculated electron capture fraction \(^{13}\); both are entered in %. Values of \( EC \), \( t \) and \( ft \) appear in columns 2, 3 and 4 of table 5.

The combined radiative corrections of order \( \alpha \), \( Z\alpha^2 \) and \( Z^2\alpha^3 \) [see eq. (5)] have been explicitly evaluated in refs. \(^{7-9}\) and the \( \delta_R \) values listed in column 5 include these calculated terms, with interpolations \(^1\) where necessary. The correction \( \delta_C \) in column 6 was taken directly from our earlier work \(^1\).

The corrected \( \mathcal{F}t \) values from table 5 yield a weighted average of:

\[
\mathcal{F}t = 3081.7 \pm 1.9 \text{ sec,} \tag{11}
\]

and a corresponding \( \chi^2 \) per degree of freedom of 0.8. The associated confidence level (defined in sect. 3) is 58% indicating that the data are now in complete concordance as can also be judged from the ideogram shown in fig. 3. The low \( \chi^2 \) reflects our procedure of inflating error limits (through the use of scale factors, see sect. 3) on weighted averages when faced with inconsistent experiment measurements.

Assuming the uncertainties in the calculated corrections \( \delta_R \) and \( \delta_C \) are small compared to the experimental error bars, then the high confidence level obtained in the weighted average indicates that an experimental verification of the CVC hypothesis has been obtained.

5. Consistency analysis

5.1. THE CORRECTIONS \( \delta_R \) AND \( \delta_C \)

We speculated in sect. 2 that the uncertainty in the calculated radiative corrections could begin at order \( Z\alpha^2 \). To search for evidence of consequent \( Z \)-dependent trends in the experimental data, a second least squares analysis of the \( \mathcal{F}t \) values was performed using the formula

\[
\mathcal{F}t = (\mathcal{F}t)_0(1 + aZ\alpha^2). \tag{12}
\]

The resulting \( \chi^2 \) per degree of freedom of 0.8 was no better than that for the fit to a constant only and the parameter "\( a \)" was not significantly determined, viz.

\[
(\mathcal{F}t)_0 = 3079.5 \pm 4.2 \text{ sec,} \quad a = 1.0 \pm 1.6. \tag{13}
\]

Clearly, there is no evidence for any lingering \( Z \)-dependence in the experimental data.

The other uncertainty speculated upon in sect. 2 concerned the correction \( \delta_C \). Since the evaluation of \( \delta_C \) depends sensitively on nuclear models, it might be argued that this correction is better omitted altogether. Refitting the data without \( \delta_C \), we obtain

\[
ft(1 + \delta_R) = 3094.2 \pm 2.1 \text{ sec,} \tag{14}
\]
with a poorer $\chi^2$ per degree of freedom, viz. 1.4. The average $f(t(1 + \delta_R))$ is 0.4% higher than the average $f(t)$ value in eq. (11).

The correction $\delta_c$ comes from electromagnetic corrections of the type shown in diagrams (c) and (c') of fig. 1, and the leading term in this correction is expected to be of order $Z^2a^2$. Thus we once again refit the experimental data to the formula

$$f(t(1 + \delta_R)) = a_0(1 + a_1 Z^2a^2), \quad (15)$$

but the $\chi^2$ per degree of freedom of 1.0 is still poorer than the original fit. The parameter $a_1$ is however determined by the fit, viz:

$$a_0 = 3089.9 \pm 2.7 \sec, \quad a_1 = 0.11 \pm 0.05. \quad (16)$$

An examination of the values of $\delta_c$, as plotted in fig. 4, shows that while $\delta_c$ increases overall with $Z$ it is not a simple monotonically increasing function, but rather has pronounced nuclear-shell effects superimposed. The experimental data appear to confirm the need for such shell structure, since the one and two parameter analyses tried without $\delta_c$ could not improve upon the original $\chi^2$.

5.2. Fierz interference term

Without experimental evidence to the contrary, there would be no reason to believe a priori that a scalar interaction could not contribute in addition to the vector interaction in allowed $\beta$-decay. Its presence would cause deviations from the statistical $\beta^+$ spectrum shape such that the shape factor $C(W)$ in eq. (9) would be
replaced by \( C(W)[1 - \gamma b_F/W] \), where \( \gamma^2 = 1 - Z^2 \alpha^2 \). The factor \( b_F \) is the conventional (Fermi) Fierz constant \(^{14}\), which is related to the ratio of scalar and vector coupling constants.

Despite detailed investigations of the energy dependence of experimental \( \beta \)-spectra, no evidence of a non-zero Fierz term has ever been produced. However, the sensitivity of such experiments to \( b_F \) is not great [see, for example, ref. \(^{15}\)] which concludes that \( b_F \leq 0.11 \) and an alternative test was proposed by Gerhart and Sherr \(^{16}\). They pointed out that with a Fierz term the \( \mathcal{F}t \) values for \( 0^+ \to 0^+ \) transitions would not be constant but would depend on the average decay energy, \( \langle W \rangle \). The dependence is given by a modified version of eq. (3), *viz.*:

\[
\mathcal{F}t \left( 1 - \frac{\gamma b_F}{\langle W \rangle} \right) = \frac{K}{2G_v^2(1 + \Delta R)}.
\]

By examining the behaviour of \( (\mathcal{F}t)^{-1} \) as a function of \( \gamma \langle W \rangle^{-1} \) Gerhart \(^{15}\) obtained an upper limit of \( b_F \leq 0.12 \). With the \( \mathcal{F}t \) value data in table 5, more than an order of magnitude improvement on this limit for \( b_F \) can be attained. A least squares fit of eq. (17) to the experimental data yields

\[
b_F = -0.001 \pm 0.006.
\]

Evidently the assumption that \( b_F \) is zero is justified in extracting an average \( \mathcal{F}t \) value. This conclusion is in accord with the two-component (massless) neutrino theory \(^{14}\), which requires that the Fierz constant \( b_F \) be exactly zero.

6. Vector coupling constant and Cabibbo universality

Having verified the internal consistency of the experimental data and theoretical corrections, we return to the "best" average \( \mathcal{F}t \) value of eq. (11) in order to derive a value for the effective vector coupling constant \( G_v \) and to discuss its implications for weak interaction theories. From eqs. (3) and (11), \( G_v \) becomes

\[
G_v = G_v(1 + \Delta R) = (1.4130 \pm 0.0004) \times 10^{-49} \text{ erg} \cdot \text{cm}^3.
\]

In Cabibbo theory \(^{17}\), the coupling constant for nuclear Fermi \( \beta \)-decay relates to that for muon decay, \( G_\mu \), through the universality relation:

\[
G_v = G_\mu \cos \theta_v,
\]

where \( \theta_v \) is the Cabibbo angle.

Recently, the parameters of Cabibbo theory have been determined \(^{18}\) from a fit to experimental data on hyperon \( \beta \)-decays. In the limit of exact SU(3) a two-parameter fit to eight data points gives a very precise value for the Cabibbo angle, *viz.*:

\[
\sin \theta_v = 0.232 \pm 0.003.
\]

Another recent development is a new and very accurate measurement of the muon
The average of this measurement with the six previous determinations yields a mean life of $\tau = 2.1977 \pm 0.0007 \mu s$. The quoted uncertainty has been inflated by a scale factor of 2.4, reflecting an inconsistency in the two most accurate data. The corresponding coupling constant for muon decay, incorporating the classical radiative correction of order $\alpha$, is

$$G_\mu = (1.43563 \pm 0.00022) \times 10^{-49} \text{ erg} \cdot \text{cm}^3.$$ (22)

Combining this value with eqs. (19) to (21), we solve for the unknown radiative correction $\Delta_R$

$$\Delta_R = (2.38 \pm 0.17)\%.$$ (23)

The significance of this result can be appreciated by examining fig. 5, in which $\Delta_R$ as calculated from eq. (6) is plotted against the parameter $M_Z$ for two different quark models. The experimentally determined $\Delta_R$, eq. (23), sets restrictive limits of $25 \leq M_Z \leq 40$ GeV for a model with four quarks of integral charge ($\rho = 1$) and $M_Z \geq 100$ GeV for three coloured quartets ($\rho = \frac{1}{3}$). Remembering that $M_Z$ is open to a variety of interpretations, we note as an example that in local V-A theories, if the mass cut-off (now $M_Z$) is of the order of a nucleon mass, the present result would violate Cabibbo universality.

![Fig. 5. Radiative correction $\Delta_R$; eq. (6) is plotted as a function of $M_Z$, the mass of the Z vector boson for the two different quark models, $\rho = 1$ and $\rho = \frac{1}{3}$. The horizontal cross-hatched area corresponds to the value of $\Delta_R$ in eq. (23), which in turn derives from the determination of the Cabibbo angle from hyperon $\beta$-decays, eq. (21). The deduced limits on $M_Z$ are indicated with solid arrows at the bottom of the figure. The dashed horizontal lines correspond to the less restrictive limits on the Cabibbo angle, eq. (24). A vertical scale corresponding to $\sin \theta_v$ is provided to the right of the figure.](image)
Contemporary theories, unifying weak and electromagnetic interactions give order-of-magnitude estimates for the mass $M_z$ of the neutral vector boson. Weinberg $^{21}$) quotes a value $M_z \gtrsim 74.6$ GeV. This is outside the limits obtained with the $\rho = 1$ quark model, but could easily be accommodated in other versions, ($\rho < 1$).

The very precise value for $\Delta R$ in eq. (23) reflects the tight limits set on $\sin \theta_V$ from the analysis of hyperon decay data. These data fit the Cabibbo theory excellently in the limit of exact SU(3). However Roos $^{18}$) also considered the possibility that renormalisation, principally due to symmetry breaking, should influence the derived Cabibbo angle. He therefore performed a four-parameter analysis that extends the range of acceptable $\sin \theta_V$ values to:

$$0.224 \leq \sin \theta_V \leq 0.252. \quad (24)$$

The corresponding experimental limits on $\Delta R$ are shown by dashed lines in fig. 5. Even with these very generous extremes, a lower limit of 15 GeV can be placed on $M_z$, still ruling out local theories with a low mass cut-off.

*Note added in proof:* It has come to our attention that an independent survey of data relevant to $0^+ \rightarrow 0^+$ superallowed $\beta$-decay has been performed by Raman et al. (Nucl. Data, to be published). Their $\delta_V$ values are substantially the same as ours, although their calculation of $\delta_C$, which used a simple harmonic oscillator model, results in a small shift in the effective vector coupling constant, $G'_V$. The overview and conclusions presented here are unaffected by this detail.

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