Super-allowed Fermi β decay: The lifetimes of $^{26}Al^m$, ^{46}V, and ^{54}Co †

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The half-lives of the Fermi super-allowed β-ray transitions from $^{26}Al^m$, ^{46}V, and ^{54}Co have been measured by multiscaling β rays detected in a plastic scintillator. The activities were made via the reactions $^{24}Mg(t,n)^{26}Al^m$ at $E_t = 3.1$ MeV, $^{46}Ti(p,n)^{46}V$ at $E_p = 10$ MeV, and $^{54}Fe(p,n)^{54}Co$ at $E_p = 10$ MeV, respectively. Results for the half-lives were as follows: $^{26}Al^m - 6339.5 \pm 4.5$ msec; $^{46}V - 422.52 \pm 0.45$ msec; and $^{54}Co - 193.28 \pm 0.18$ msec. A previously published experiment on the ^{46}V half-life has been reanalyzed and found to be in agreement with the present work. Recommended values for the half-lives of the eight accurately measured super-allowed Fermi β emitters are presented. We discuss the effect of arbitrary symmetry breaking in gauge theories on the extraction of the mean quark charge and conclude that the associated uncertainty is unlikely to be large.

[RADIOACTIVITY $^{26}Al^m$, ^{46}V, ^{54}Co; measured $T_{1/2}$; compared with systematics.]

I. INTRODUCTION

The vector coupling constant effective for nucleon β decay may be most directly derived from $J^\pi = 0^+ \to 0^+$ transitions within isospin multiplets. In order to extract the coupling constant with high precision both the energy release in the β decay and the lifetime of the decay must be known with appropriate accuracy. If our aim is at an overall accuracy of the order of 0.1% or better, as is justified by the uses to which the information may be put,[1] it seems that we are at present restricted to eight candidates: ^{14}O, $^{26}Al^m$, ^{34}Cl, $^{38}K^m$, ^{42}Sc, ^{46}V, ^{50}Mn, and ^{54}Co. We have recently[1] measured the lifetimes of five of these bodies, namely ^{34}Cl, $^{38}K^m$, ^{42}Sc, ^{46}V, and ^{50}Mn. This paper reports the continuation of our program of such measurements by the addition of the lifetimes of $^{26}Al^m$ and ^{54}Co and the remeasurement of that of ^{46}V.

We shall take the opportunity of summarizing what we regard as "best values" for the lifetimes of the eight bodies in question. We shall not now attempt a fresh overall analysis of the situation but shall add a few comments to our recent discussion[1] of the implication of such measurements for radiative corrections and, in particular, quark charges.

II. EXPERIMENTAL METHODS

$^{26}Al^m$

The target for producing $^{26}Al^m$ was made by reducing MgO, enriched to 99.94% in ^{24}Mg, to the metal which was then rolled to a foil 0.004 cm thick. The foil was clamped in a "rabbit" and bombarded with 3.1-MeV tritons from the 3.5-MeV Van de Graaff to make $^{26}Al^m$ in the $^{24}Mg(t,n)^{26}Al^m$ reaction. Following a 4-sec bombardment at a beam current of 1.5 nA, the sample was transferred to the control room where the β rays passed through a 45-mg/cm^2 thick Be window on the side of the transfer tubing and were detected in a 5-cm diam by a 2.5-cm thick NE102 scintillator. Background activities from the bombardment of other stable isotopes of magnesium and from oxygen were essentially eliminated by the use of the enriched metallic sample.

After a delay sufficiently long to eliminate completely the "settling-down" effect to be discussed below in connection with our earlier[1] measurements on ^{46}V, β rays were multiscaled, following standard procedures,[1] at a rate of 0.5 sec per channel for 256 channels. Thirteen runs were made at β biases from 0.5 to 2.25 MeV and with total counts in the first channel varying from 14 000 to 29 000. The long-lived background per channel in the last 30 channels of each run was typically 0.015% of the rate in the first channel. As described in Sec. III, corrections were made for pileup effects and computer fits were made starting in channels 1 and 14. One run at 0.5-MeV bias seemed to have been affected by the presence of annihilation radiation and one run at the highest bias, 2.25 MeV, was too close to the β end point to be considered reliable. Results from these two runs were not used in obtaining the final average value.

^{46}V

^{46}V was made in the $^{46}Ti(p,n)^{46}V$ reaction by using a target of $^{46}TiO_2$, enriched to 82.4% in ^{46}Ti, and deposited on a thick Ta backing. This was placed in a thin-walled glass target chamber and bombarded for 0.5 sec with a beam of 10-MeV protons from one of the MP Tandem Van de Graaffs. The NE102 detector was placed close to the target chamber and β rays were multiscaled at 0.03 sec/channel for 256 channels. Various beam currents from 2 to 15 nA resulted in acceptable counting rates. Bombardment of the reverse side of the target gave no effect above background at the β biases used for the lifetime analyses.

Eleven runs were made on ^{46}V at biases ranging from 1 to 3 MeV and with total counts in the first channel varying from 15 000 to 47 000. It was clear from attempts to make two-component computer fits, consisting of the ^{46}V and a long-lived background, that a third component was present of about 4-sec half-life. Since the spectroscopic analysis given for the TiO_2 sample had listed a 0.1% contaminant of silicon, the background was presumed to be due to ^{29}P resulting from the $^{29}Si(p,n)^{29}P$ reaction. When three-component fits were made using $T_2 = 4.21$ sec for the ^{29}P activity then the results, corrected for pileup, were consistent for analyses of the various runs. The relative initial strength of the ^{29}P was bias dependent, as expected from its end-point energy of 3.95 MeV as compared with the 6.05-MeV end-point energy of ^{46}V. The ^{29}P strength varied from 0.36% of the ^{46}V in the first channel at low bias to 0.08% at high bias.

^{54}Co

A target of $^{54}Fe_2O_3$, enriched to 96.8% in ^{54}Fe, was deposited on a thick Ta backing and bombarded with 10-MeV protons to make ^{54}Co in the $^{54}Fe(p,n)^{54}Co$ reaction using the same setup and procedures as in the ^{46}V case. The bombardment time was 0.5 sec and the channel advance rate was 0.02 sec/channel for 256 channels. Beam currents were from 7.5 to 15 nA. Target-reversed bombardments, as for ^{46}V, showed no effect. Thirteen runs were made on ^{54}Co at β-ray biases from 1.5 to 3.5 MeV. Counts in the first channel varied from 16 000 to 32 000 in the different runs.

III. ANALYSIS

The analysis of the data followed our earlier procedures[1] with one exception: the correction for pileup. We earlier[1] followed the theoretical[2] analysis in which the β spectrum is assumed to be of the simple form $W^2(W_0 - W)^2$, in conventional notation, cut off by whatever thickness of absorber intervened between source and plastic detector. Our present analysis has followed the principles of the old, but instead of assuming the above theoretical form for the energy deposited in the detector we measured the spectrum of pulses in each case and fitted it empirically to the form (polynomial in W) $\times$ [polynomial in $(W_0 - W)$], then used this form in the pileup analysis in exactly the same manner as done before[2] for the theoretical form. The analytical expressions involved, while trivial to derive, are exceedingly cumbersome and opaque and we do not quote them here. Ambiguities arise at the low-pulse-height end of the spectrum but extreme assumptions as to the form of the spectrum in the region not accessible to direct determination nowhere made significant differences to our final lifetimes. In the following we call these extreme assumptions "high" and "low"; "high" means a horizontal extrapolation of the pulse-height spectrum into the inaccessible region, "low" means a linear extrapolation to the origin.

We now make some observations on the individual bodies.

$^{26}Al^m$: The "high" and "low" results for this half-life were respectively 6339.8 ± 3.2 and 6339.2 ± 3.2 msec, with respective χ^2/ν values of 0.47 and 0.43. After inflation of the error according to our usual practice[1] we quote 6339.5 ± 4.5 msec.

^{46}V: In the same sequence as above for $^{26}Al^m$, we find: 422.68 ± 0.33 and 422.36 ± 0.33 msec with χ^2/ν values of 0.61 and 0.48; quote 422.52 ± 0.45 msec.

^{54}Co: As above, we find: 193.39 ± 0.10 and 193.16 ± 0.10 msec with χ^2/ν values of 0.65 and 0.69; quote 193.28 ± 0.18 msec.

Before continuing we must make some observations about ^{46}V. Our recent measurement[1] of this half-life was 424.01 ± 0.47 msec, which one sees to be grossly inconsistent with our present value. Our previous result, combined with the value for the energy release current at that time,[3] gave an *ft* value in excellent agreement with the others of the $0^+ \to 0^+$ set. However, it later transpired[4,5] that the energy release that we used[3] is seriously in error and that the better value[4,5] combined with our previous lifetime[1] would throw the ^{46}V *ft* value out of line with the rest. Indeed, a more recent[4] measurement of the ^{46}V lifetime, namely 422.28 ± 0.23 msec, disagreed significantly with our earlier[1] value. It was this disturbing situation that led us to our present remeasurement, although our earlier one[1] had appeared to be quite satisfactory under the usual tests. We have therefore carried out a detailed reanalysis of our earlier data on ^{46}V.

Unique among our earlier measurements,[1] that for ^{46}V was carried out using a "rabbit" that transported the irradiated sample from its irradiation position to its counting position. A hazard in the use of a rabbit for the determination of short lifetimes is that the sample may take some little time to settle down to its equilibrium position in front of the counter. If counting begins during this "settling-down" period the counting efficiency will be changing as a function of time, so the deduced lifetime may be wrong. The records of our earlier[1] ^{46}V measurements permit us to test this hypothesis of a "settling-down" effect. Our earlier[1] result of 424.01 ±0.47 msec ($\chi^2/\nu = 1.29$) becomes 422.47 ±0.54 msec ($\chi^2/\nu = 1.22$) if we begin the time analysis 0.15 sec later and 422.31 ±0.77 msec ($\chi^2/\nu = 0.64$) if we begin analysis 0.48 sec later. (These quoted errors are all inflated to "95% confidence" values.[1]) These results are strongly suggestive of a "settling-down" time of about 0.1 sec or less. We can make a simple illustrative model to see if it is quantitatively reasonable. Suppose the counting efficiency varies as $1-\epsilon e^{-\gamma_s t}$, where $1/\gamma_s$ is the "settling-down" time. The apparent half-life will then be lengthened over the true half-life by the factor $1+\epsilon\lambda/\lambda_s$, which would be about 1.0035 by comparison of our previous[1] and present results. With $1/\lambda_s \simeq 0.05$ sec we should therefore need $\epsilon \simeq 5\%$, which seems quite reasonable. It seems that we might, from our previous measurements, use a half-life of 422.31 ±0.77 msec which we therefore combine with our present value of 422.52 ±0.45 msec to quote 422.47 ±0.39 msec as the Brookhaven value.

IV. RESULTS

We now compare our present results with earlier measurements and recommend "best" values. We start from the values adopted in Table I of our earlier work,[1] where the references and rationale are given. Table I of the present paper presents our conclusions. As is seen, our present values are all consistent with those earlier recommended[1] and have simply been combined with them to yield our new adopted values.

V. DISCUSSION

As remarked earlier, we shall not here repeat the discussion of the analysis that we gave before[1] in terms of the "inner" radiative correction $\Delta^{\alpha}_{\beta V}$ and the mean quark charge $\overline{Q}$ of the nucleon. We note, however, that in the meantime there have been developments both in the evaluation of the nuclear mismatch between the initial and final states[6,7] and, most importantly, in the determination of the energy release in the β decay.[5] The upshot[7] of this new work is that the value of the effective vector coupling constant that we earlier recommended[1] is virtually unchanged and therefore also the value

$$\Delta^{\alpha}_{\beta V} - \Delta^{\alpha}_{\mu} = (2.09 \pm 0.16)\%$$

for the difference between the "inner" radiative corrections of the nucleon and muon.

TABLE I. Half-lives in msec of the eight accurately measured super-allowed Fermi β emitters. With the exception of ^{46}V the value appearing in the Previous column is that recommended in our previous survey (Ref. 1); the ^{46}V value is that of Ref. 4. The Present column contains the data newly reported in this paper. An asterisk in the Adopt column means that we recommend the Previous value.

Body	Previous	Present	Adopt
^{14}O	705 92 ± 31	···	*
$^{26}Al^m$	6346.5 ± 3.5	6339.5 ± 4.5	6343.9 ± 2.8
^{34}Cl	1525.4 ± 1.0	···	*
$^{38}K^m$	922.3 ± 1.1	···	*
^{42}Sc	680.98 ± 0.62	···	*
^{46}V	422.28 ± 0.23	422.47 ± 0.39	422.33 ± 0.23
^{50}Mn	282.75 ± 0.20	···	*
^{54}Co	193.14 ± 0.23	193.28 ± 0.18	193.23 ± 0.14

Our earlier[1] discussion of the implication for $\overline{Q}$ of the above quantity was conducted in terms of Sirlin's formula[8] that was derived on the basis of the Salam-Weinberg version of gauge theory that contains only a single Higgs scalar so that the masses m_W and m_Z of the charged and neutral intermediate vector bosons are uniquely related via the Weinberg angle θ_W: $m_W = m_Z \cos\theta_W$. We took a range of m_Z, the only intermediate vector boson mass entering into Sirlin's formula, safely limited by experiment within the Salam-Weinberg framework, to find $\overline{Q} = 0.17 \pm 0.06$. Sirlin's formula was also restricted to certain classes of quark model of the nucleon.

More recently,[9] Sirlin has generalized his radiative correction formula both to include arbitrary symmetry breaking such as would correspond to a multiplicity of Higgs scalars and also to allow a wider range of quark model. Sirlin now finds[9]:

$$\Delta^{\alpha}_{\beta V} - \Delta^{\alpha}_{\mu} = \frac{\alpha}{2\pi}\left[3\ln\frac{m_W}{m_N} + 6\overline{Q}\ln\frac{m_W}{m_A} + 2C + \frac{3}{2}\,\frac{R\ln R}{R-1}\tan^2\theta_W(1+2\overline{Q})\right],$$

where m_N is the nucleon mass, $m_W = 37.3$ GeV/$\sin\theta_W$, m_A is an axial mass that, as before,[1] we take to be 1.3 GeV. C is a nonasymptotic piece, probably of order unity, that we neglected before and now do again. $R = (m_W/m_Z)^2$ and may be arbitrarily small or large depending on the details of the symmetry breaking.

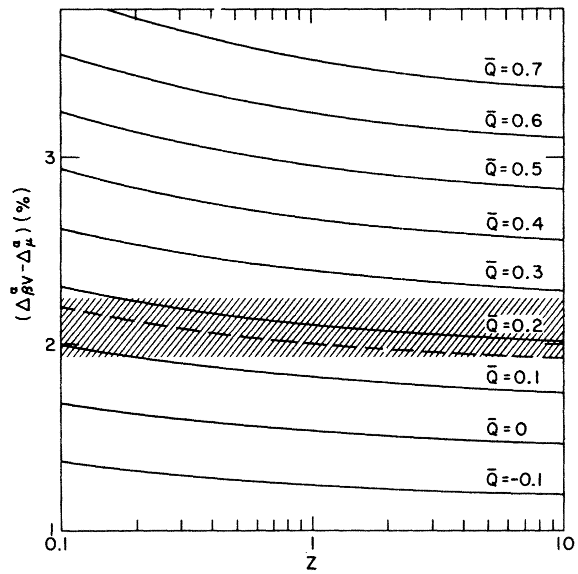

FIG. 1. The theoretical difference between the inner radiative corrections for nucleon and muon vector β decay for various mean nucleon quark charges $\bar{Q}$ as a function of the symmetry-breaking parameter $z = m_Z^2 \cos^2\theta_W/m_W^2$. The dashed line is for $\bar{Q}=\frac{1}{6}$ and the shaded band is the experimental result.

We see that the difference of the inner radiative corrections no longer determines $\bar{Q}$ uniquely in terms of θ_W. The sensitivity to R is, however, weak. We illustrate this using the popular value $\sin^2\theta_W=\frac{3}{8}$ when the above expression takes the numerical value

$$\frac{\alpha}{2\pi}(12.5+23.1\bar{Q}+0.9x+1.8\bar{Q}x).$$

Here $x=R\ln R/(R-1)=[\ln(5/8z)]/(1-1.6z)$, where $z=m_Z^2\cos^2\theta_W/m_W^2$ is a measure of the departure of the symmetry breaking from that of a single Higgs scalar for which $z=1$. Figure 1 shows the above expression as a function of z for various values of $\bar{Q}$ together with the experimental value. Since there is some experimental indication that z may not be far from unity[10] our conclusion as to $\bar{Q}$ is not strongly influenced by uncertainty about the symmetry breaking. We must recall, however, that our neglect[1] of the effect of SU(3) symmetry breaking in the extraction of the Cabibbo angle from hyperon decay could seriously affect our conclusion about $\bar{Q}$. We may also note that although the nonasymptotic piece C is probably small it may not be negligible. If it were indeed of order unity[8,9] it would shift the theoretical curves of Fig. 1 upwards by about 0.2% in $\Delta^{\alpha}_{\beta V}-\Delta^{\alpha}_{\mu}$, viz, by about the same as the experimental error in that quantity. Use of the theoretical estimate[11] for the SU(3) symmetry-breaking correction to the Cabibbo angle would move the experimental value of $\Delta^{\alpha}_{\beta V}-\Delta^{\alpha}_{\mu}$ up by about 0.4%. So these two corrections to the overall analysis, both of uncertain magnitude, at least tend to cancel.

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