PREPRINT

tascc

**THE ^{10}C SUPERALLOWED BRANCHING RATIO
AND THE CABIBBO-KOBAYASHI-MASKAWA
MATRIX UNITARITY**

**G. Savard, A. Galindo-Uribarri, E. Hagberg, J.C. Hardy,
V.T. Koslowsky, D.C. Radford and I.S. Towner**

AECL, Chalk River Laboratories, Chalk River, Ontario, K0J 1J0, Canada

Presented at
International Conference
on Exotic Nuclei and
Atomic Masses
Arles, France
1995 June 19-23

CERN LIBRARIES, GENEVA
SCAN-9508116

NOTICE

This report is not a formal publication; if it is cited as a reference, the citation should indicate that the report is unpublished. To request copies our E-Mail address is **TASCC@CRL.AECL.CA**.

Physical and Environmental Sciences
Chalk River Laboratories
Chalk River, ON K0J 1J0 Canada

1995 June

500933

THE ^{10}C SUPERALLOWED BRANCHING RATIO AND THE CABIBBO-KOBAYASHI-MASKAWA MATRIX UNITARITY

G. Savard, A. Galindo-Uribarri, E. Hagberg, J.C. Hardy, V.T. Koslowsky,
D.C. Radford and I.S. Towner
AECL, Chalk River Laboratories, Chalk River, Ontario, Canada, K0J 1J0.

ABSTRACT

A measurement of the superallowed $0^+ \rightarrow 0^+$ branching ratio in ^{10}C , performed with the 8π gamma-ray spectrometer, is described. From the measured branching ratio, we extract a new precise value of $\mathcal{F}t(^{10}\text{C}) = 3074.4(5.4)$ s. This does not support previously suggested Z - or Z^2 -dependent terms in the fit to the superallowed $0^+ \rightarrow 0^+$ data set, which removed the apparent non-unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix.

The nucleus is a valuable testing ground for the electroweak sector of the standard model. In particular, superallowed $0^+ \rightarrow 0^+$ nuclear β -decay ¹⁾ between isobaric analogue states provide the best test of the Conserved Vector Current (CVC) hypothesis, the most accurate value of G_v (the weak vector coupling constant) and, together with the muon lifetime, the most accurate value for the up-down quark-mixing matrix element of the CKM matrix, V_{ud} . According to the Conserved Vector Current (CVC) hypothesis, all such decays should yield the same value of G_v from their measured ft -values providing that small isospin-symmetry-breaking (δ_c) and radiative (δ_r) corrections are accounted for. Specifically, for an isospin-1 multiplet,

$$ft(1 + \delta_r)(1 - \delta_c) \equiv \mathcal{F}t = \frac{K}{2G_v^2}. \quad (1)$$

The $\mathcal{F}t$ -values for the eight precisely measured such decays ²⁾ are shown as solid points in figure 1. From these data, an average $\mathcal{F}t$ value of $3072.2(2.1)$ s is obtained¹⁾. With G_v determined from this result and combined with the purely leptonic muon decay data, we obtain the value $V_{ud}=0.9740(0.0005)$. Finally, taking values for V_{us} and V_{ub} from ref. ³⁾, we

find

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9972(0.0013) \quad (2)$$

Thus, although the data displayed in figure 1 show that the agreement among the eight $\mathcal{F}t$ -values supports the CVC hypothesis, the value of V_{ud} extracted from the mean $\mathcal{F}t$ -value results in a unitarity test of the first row of the CKM matrix which differs from unity by more than two standard deviations. Two- and three-parameter fits⁴⁾ have been proposed (see figure 1) to take into account possible systematic trends in the $\mathcal{F}t$ -values by the arbitrary addition of fitted Z - or Z^2 -dependent terms in the analysis. The resulting extrapolated $\mathcal{F}t(Z=0)$ value would then meet the unitarity requirement. To establish whether such phenomenological fitting can be justified, an experiment was mounted to provide a new data point closer to $Z=0$ namely that of the lightest superallowed $0^+ \rightarrow 0^+$ β -decay emitter, ^{10}C .

Figure 1: The solid points are the $\mathcal{F}t$ values for the eight precisely measured superallowed $0^+ \rightarrow 0^+$ β -decay emitters²⁾ plotted as a function of the Z of the daughter nuclei. The open point is the new ^{10}C $\mathcal{F}t$ -value. The full line is the result of the one-parameter fit to the data set before the addition of the ^{10}C point. The dashed (dotted) lines are the corresponding best two- (three-) parameter fits.

The decay of ^{10}C takes place mainly through a strong Gamow-Teller transition to an excited 1^+ state in ^{10}B while only about 1.5% of the decay strength goes to the isobaric analogue 0^+ state (see figure 2a). The superallowed branching ratio is simply given by the ratio of the number of gamma rays emitted at 1022 keV over that at 718 keV, i.e.

$$BR(0^+ \rightarrow 0^+) = \frac{R(1022)}{R(718)} = \frac{Y(1022)}{Y(718)} \frac{\epsilon(718)}{\epsilon(1022)}, \quad (3)$$

with R being the emission rate, Y the observed yield and ϵ the efficiency at a given energy. Any measurement, however, requires excellent statistics to yield precision of a few parts per thousand on such a weak branch. In addition, since the isobaric analogue state is deexcited by the emission of a 1022 keV gamma ray, it is also necessary to minimize and account for the pile-up of 511 keV annihilation radiation.

The 511 keV pile-up rate compared to the real 1022 keV gamma ray rate is given by the simple expression

$$\frac{Y(\text{pile-up})}{Y(1022)} \approx \frac{R^2(511)\epsilon^2(511)\Delta\tau}{R(1022)\epsilon(1022)} \quad (4)$$

with $\Delta\tau$ being the resolving time of the pile-up rejection system. If the same total detector efficiency is now split in N independent detectors, this ratio is decreased by a factor N :

$$\left(\frac{Y(\text{pile-up})}{Y(1022)} \right)_N \approx \frac{NR^2(511)(\epsilon(511)/N)^2\Delta\tau}{NR(1022)(\epsilon(1022)/N)} \approx \frac{1}{N} \frac{Y(\text{pile-up})}{Y(1022)}. \quad (5)$$

The experiment was therefore performed on a large gamma-ray array, the 8π spectrometer⁵), at Chalk River. The spectrometer is composed of 20 Compton-suppressed 25% HPGe detectors surrounding a 72-element BGO inner ball. The array is equipped with individual pile-up rejection system on the germanium detectors, further adding to the pile-up reduction provided by the geometry of the array.

The experiment comprised two interleaved measurements. One, the relative gamma-ray yield measurement, was a repeated cycle in which the activity was first produced by a (p,n) reaction on a gold-backed enriched $550\mu\text{g}/\text{cm}^2$ ^{10}B target mounted in the center of the 8π spectrometer, and then the beam was turned off and the β -delayed gamma rays from the decay of ^{10}C observed in singles mode (fig. 2a). The second measurement, that of the relative gamma-ray efficiency, was performed in-beam with γ - γ coincidences recorded from the deexcitation of the 2.154 MeV level in ^{10}B , which was populated by the (p,p') reaction. The main decay channel of the 2.154 MeV level, populated in-beam, involves the sequential emission of

Figure 2: a) Decay scheme of ^{10}C . The ground state and 2.154 MeV levels both have negligible direct feeding in the decay⁶). b) Main deexcitation route for the 2.154 MeV level.

three gamma rays of energies 414, 1022 and 718 keV respectively (figure 2b). The ratio of the number of $\gamma_{414} - \gamma_{718}$ coincidences over $\gamma_{414} - \gamma_{1022}$ coincidences is therefore equal to the efficiency ratio $\epsilon(718)/\epsilon(1022)$ required in eq (3).

The experiment was performed over two one-week periods. During the runs, 25 cycles of 30-s-collection/ 30-s-decay measurements were interleaved with segments of 30 minutes in-beam efficiency calibration. An 8 MeV proton beam intensity of roughly 100 nA was used in the collection/decay mode while the intensity was reduced to about 15 nA for the in-beam calibration. The total statistical uncertainty was about 1.4×10^{-3} . A β -delayed gamma-ray spectrum from ^{10}C decay and a spectrum of in-beam gamma rays coincident with the 414 keV transition obtained over a one-week period are shown in figure 3.

Some small corrections must be applied to the raw experimental numbers. They are listed in table 1 and elaborated as follows: 1) The 511 keV pile-up correction in the decay measurement, which was of the order of 10 % in all previous measurements of this branching ratio⁷⁻⁹), is reduced to a 0.01 % correction by the new technique used here. 2) Contamination in the counting sample is a serious concern in the decay measurement, especially for the weaker 1022 keV peak. The decay data were tagged by the time after the collection so that separate

analyses could be performed for different decay-time slices. No variation in the gamma ray yield ratio $Y(1022)/Y(718)$ was observed, setting a limit of 2×10^{-3} on possible contamination. In addition, background spectra were also recorded to determine the room background and the isotopes produced by the gold backing. No evidence for an unresolved contamination of the peaks of interest was

Table 1. Experimental corrections to be applied to the branching ratio.

	Source of effect	size	affects
1	511 pile-up	$-0.9(2) \times 10^{-4}$	decay data
2	background	0	decay data
3	1.740 MeV $\rightarrow$ g.s.	$0^{(+1.1)}_{(-0)} \times 10^{-4}$	decay data
4	internal conversion	$< 10^{-6}$	both
5	angular correlation	0	in-beam data
6	kinematics shift	$< 10^{-4}$	in-beam data
7	random coincidences	$< 10^{-4}$	both
8	pile-up + suppressors	$6.5(8) \times 10^{-3}$	both

observed. 3) An upper limit of 9×10^{-5} is obtained from this experiment for the deexcitation of the 1.740 MeV state directly to the ground state. This results in a correction of up to 1.1×10^{-4} . 4) Internal conversion is a negligible correction and, in any case, cancels out in the ratio. 5) No angular-correlation corrections are necessary in the $\gamma_{414} - \gamma$ data since the 414 keV gamma ray populates a 0^+ state. 6) For the in-beam data, the 414 and 1022 keV gamma rays are emitted during the slowing-down process, while the 718 keV gamma rays are emitted essentially at rest. A small correction must therefore be applied for the kinematic change in solid angle and efficiency (from the energy shift) for the different detectors. The maximum kinematic correction is $+(-) 0.8 \times 10^{-3}$ for the most forward (backward) ring of the 8π spectrometer HPGe detectors, which cancels out when the spectra from all rings of detector are summed. 7) Effects of random coincidences on the $\gamma_{414} - \gamma$ data have been removed by subtraction of counts obtained in a non-coincident time gate.

Figure 3: The top spectrum, obtained in the decay measurement, contains peaks from room background, from activity created by the beam (mostly ^{10}C) and from activity induced by neutrons. The lower spectrum shows gamma rays in coincidence with a 414 keV gamma ray in-beam. The two strong peaks are the 718 and 1022 keV peaks of interest. The broad peak at 1433 keV is from a gamma ray feeding the 2.154 MeV state.

The final correction to consider (#8) is the effect of pile-up. Pile-up due to randoms

does not affect the ratios measured. The main concern comes from pile-up losses due to the many gamma rays emitted in each event. For example, when the 2.154 MeV state in ^{10}B is populated in-beam and valid 414 and 718 keV gamma-ray events are registered in two detectors, the 1022 keV gamma ray which is also emitted in this event could invalidate the event if it deposits any energy in one of these two detectors. Furthermore, since each HPGe detector has associated with it a large BGO Compton suppressor, the additional gamma ray could also veto the event by depositing energy in one of the two suppressors. The effect of this type of event has been investigated with standard sources that emit two gamma rays, the gamma-ray spectrum being recorded with the acquisition electronics modified so that half of the HPGe detectors *required* a suppressor signal for the event to be valid. A valid photopeak event in one of the modified detectors then implied that another γ -ray deposited energy in the corresponding suppressor but none in the detector itself. These measurements yield a correction of $+6.5(8) \times 10^{-3}$ for the branching ratio. The largest contribution comes from the decay events, in which emission of a 1022 keV gamma ray is always accompanied by a 718 keV gamma ray, while a 718 keV gamma ray only has a 1022 keV gamma ray emitted with it 1.5% of the time.

With all corrections applied, we determine the total branch to the isobaric analogue state to be

$$BR(0^+ \rightarrow 0^+) = (1.4625 \pm 0.0020(stat) \pm 0.0015(syst))\% \quad (6)$$

where the systematic uncertainty is the one attributed to the sum of all experimental corrections; it should be added quadratically to the statistical uncertainty. This result agrees with, but is substantially more precise than, previous measurements⁷⁻⁹). When averaged together and combined with Q_{EC} (for the superallowed transition) = 1907.77(9) keV¹⁰) and $t_{1/2} = 19.290(12)$ s¹¹), and corrected for electron capture (0.296%), $\delta_c = 0.16(3) \%$ ²) and $\delta_r = 1.30(4) \%$ ² $\mathcal{F}t(^{10}\text{C}) = 3074.4(5.4)\text{s}.$ ⁽⁷⁾

This result favors the standard one-parameter analysis compared to the two- and three-parameter fits to the complete set of $\mathcal{F}t$ -values (figure 1). Table 2 shows the parameters obtained for the three analysis procedures with and without the ^{10}C data. The reduced χ^2 for the standard one-parameter analysis is significantly reduced by the addition of the new data point and the extracted $\mathcal{F}t(Z=0)$ is not affected; the non-unitarity therefore remains. For the two-parameter approach, the quality of the fit is slightly worse as is the agreement with unitarity. The three-parameter fit suffers from a large increase in the reduced χ^2 and both a_i parameters are consistent with null values. An F-test statistical analysis to determine the need for additional free parameters rejects the three-parameter fit.

The addition of ^{10}C to the set of precisely measured superallowed $0^+ \rightarrow 0^+$ β -decay emitters therefore does not support the existence of Z -dependent corrections unaccounted for by δ_r and δ_c . Consequently it also leaves the CKM unitarity condition unsatisfied. Possible explanations of non-unitarity include the “trivial” (possibly an inadequate evaluation of V_{us}

¹²⁾ for example) as well as more profound extensions to the standard model.

References

1. J.C. Hardy, I.S. Towner, V.T. Koslowsky, E. Hagberg and H. Schmeing, Nucl. Phys. A509, 429 (1990).
2. I.S. Towner et al., "Superallowed Fermi beta decay - A status report", these proceedings.
3. Particle Data Group, Phys. Rev. D50, 1173 (1994).
4. D.H. Wilkinson, Nucl. Inst. and Meth. A335,201 (1993).
5. J.P. Martin et al., Nucl. Inst. and Meth. A257, 301 (1987).
6. D.R. Goosman and D.E. Alburger, Phys. Rev. C5, 1893 (1972).
7. D.C. Robinson, J.M. Freeman and T.T. Thwaites, Nucl. Phys. A181, 645 (1972).
8. Y. Nagai et al., Phys. Rev. C43, R9 (1991).
9. M.A. Kroupa, S.J. Freedman, P.H. Barker and S.M. Ferguson, Nucl. Inst. and Meth. A310, 649 (1991).
10. S.C. Baker, M.J. Brown and P.H. Barker, Phys. Rev. C40, 940 (1989).
11. G. Azuelos et al., Phys. Rev. C9, 1213(1974); P.H. Barker and G.D. Leonard, Phys. Rev. C41, 246 (1990).
12. A. Garcia, R. Huerta and P. Kielanowski, Phys. Rev. D45, 879 (1992).

Table 2. Fitted value of $\mathcal{F}t(Z=0)$ and other parameters from one-, two- and three-parameter fits. Also given are the χ^2 values and the resulting unitarity tests. The first column is for the data set without ^{10}C , the second column includes the new ^{10}C value.

	data set without ^{10}C	data set with ^{10}C
1-parameter fit		
$\mathcal{F}t(0)$	$3072.2 \pm 2.1 \text{ s}$	$3072.3 \pm 2.0 \text{ s}$
χ^2/N	1.49	1.20
V_{ud}	0.9740 ± 0.0005	0.9736 ± 0.0006
$\sum_i V_{ui}^2$	0.9973 ± 0.0013	0.9965 ± 0.0015
2-parameter fit		
$\mathcal{F}t(0)$	$3067.3 \pm 3.5 \text{ s}$	$3068.3 \pm 3.3 \text{ s}$
a_1	$(0.9 \pm 0.5) \times 10^{-4}$	$(0.7 \pm 0.5) \times 10^{-4}$
χ^2/N	1.01	1.00
V_{ud}	0.9748 ± 0.0007	0.9746 ± 0.0007
$\sum_i V_{ui}^2$	0.9988 ± 0.0015	0.9985 ± 0.0015
3-parameter fit		
$\mathcal{F}t(0)$	$3065.0 \pm 7.6 \text{ s}$	$3068.8 \pm 10.9 \text{ s}$
a_1	$(1.9 \pm 2.9) \times 10^{-4}$	$(0.5 \pm 2.6) \times 10^{-4}$
a_2	$(-0.3 \pm 0.9) \times 10^{-5}$	$(0.1 \pm 0.8) \times 10^{-5}$
χ^2/N	1.18	1.17
V_{ud}	0.9751 ± 0.0022	0.9745 ± 0.0018
$\sum_i V_{ui}^2$	0.9995 ± 0.0043	0.9983 ± 0.0036