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IN SUPERALLOWED $0^+ \rightarrow 0^+$ β DECAYS***

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Abstract

Measurements of superallowed $0^+ \rightarrow 0^+$ nuclear β decays, corrected for radiative and charge-dependent effects yield fundamental properties of the weak interaction. Model predictions of the necessary corrections exist, but they have never been tested directly by experiment. The present work reports, for the first time, observations of (or limits on) non-analogue $0^+ \rightarrow 0^+$ branches in $^{38\text{m}}\text{K}$, ^{46}V , ^{50}Mn and ^{54}Co , and tests of the model predictions for isospin-mixing corrections. The resulting unitarity test of the top row of the K-M matrix is 0.9983 ± 0.0015 .

Studies of superallowed nuclear β decays between analogue 0^+ states provide data that permit stringent tests of the properties of the electroweak interaction[1-3]. These studies are attractive because, to the extent that isospin is a conserved quantum number, there is a very simple relation between the weak vector coupling constant and the measured ft values for such decays. In reality, some complications arise because bremsstrahlung and related processes need to be accounted for through radiative corrections [2,4,5] and because Coulomb and charge-dependent forces do, in fact, break the isospin symmetry [6-8]. When calculated corrections are included to account for these effects, the corrected ft value, denoted $\mathcal{F}t$, is related to the effective weak vector coupling constant, G'_V , as follows (for $T=1$ states):

$$\mathcal{F}t = ft (1+\delta_R) (1-\delta_C) = \frac{K}{2 G'_V{}^2} \quad (1)$$

where f is the statistical rate function, t is the partial half-life for the transition, δ_R is the calculated radiative correction, δ_C the calculated isospin symmetry-breaking correction and K is a known constant [1].

Superallowed nuclear β transitions are examples of semi-leptonic weak decay and the value for G'_V obtained from them can, when combined with the value obtained from the purely leptonic muon decay, yield a value for the V_{ud} quark mixing element of the Kobayashi-Maskawa (KM) matrix (see for example [1]). Tests of the unitarity of this matrix, for instance

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1, \quad (2)$$

establish limits to extensions of the Standard Model such as the existence of additional gauge bosons or right-handed currents [2]. Unfortunately, the value for G_V' deduced from an average of the eight most precisely known superallowed $0^+ \rightarrow 0^+$ β emitters, ^{14}O , ^{26}mAl , ^{34}Cl , ^{38}mK , ^{42}Sc , ^{46}V , ^{50}Mn and ^{54}Co , disagrees by several standard deviations with the value obtained from the decay of the neutron [9,10].

The $\mathcal{F}t$ and G_V' values deduced from nuclear β decays are statistically much more precise than those deduced from the neutron decay. However, there is some room, albeit small, for different interpretations of the β -decay data. In accordance with the Conserved Vector Current hypothesis, the $\mathcal{F}t$ values for all eight β -decay cases should be identical; the best, overall $\mathcal{F}t$ value should thus be obtained from an average of the eight individual cases [1,2]. An alternative interpretation of the data, however, makes the assumption that there is a residual Z dependence in the $\mathcal{F}t$ values due to processes not accounted for in the usual δ_c correction; in that case, the best overall $\mathcal{F}t$ value is taken from a curve fitted to the eight individual points and extrapolated to $Z=0$ [3,11]. With G_V' deduced from β decays, the unitarity condition (eq. 2) is less than one in one-parameter fits, but is met in two-parameter fits; it exceeds one if the neutron G_V' value is used.

In order to pursue issues like these, one must examine the two correction terms in eq. 1. By far, the largest contribution to the $\mathcal{F}t$ -value uncertainty come from the calculations of δ_c and δ_R , not from the experimental data.

The charge-dependent correction, δ_c , in particular, reflects differences between the initial- and final-state wave functions, and thus is strongly nuclear-structure dependent. The two most complete calculations of this correction, which use the Towner-Hardy-Harvey model, THH [1,6,7], and the Ormand-Brown model, OB [8], show qualitative agreement in that the large variations in δ_c from nucleus to nucleus are similar for both models. However, the models differ in their values for the absolute magnitude of the correction.

Both models identify two separate contributions to the charge-dependent correction. The larger, radial-overlap part, δ_{RO} , arises from the fact that protons are less bound than neutrons, so the (initial) proton wave-function imperfectly overlaps the (final) neutron one. The smaller, isospin-mixing part, δ_{IM} , results from the different degrees of configuration mixing in the wave-functions of members of an isospin multiplet.

This paper describes a series of experiments that yield, for the first time, systematic data to test the δ_{IM} model predictions. For a $0^+ \rightarrow 0^+$ superallowed β decay, the analogue initial and final states are both

subject to isospin mixing because of the presence of charge-dependent forces. The mixing produces a reduction in the overlap for the analogue-state transition that depends on the difference between the mixing in the parent and that in the daughter. The mixing also permits vector β -decay branches to non-analogue 0^+ states, processes that are expressly forbidden unless those states contain an admixture of the analogue configuration. The magnitude of such non-analogue $0^+ \rightarrow 0^+$ branches thus reflects information on the isospin-mixing correction, δ_{IM} . If we denote the (Fermi) matrix element for the ground-state transition as $\langle M_0 \rangle$ and that for the non-analogue transition to an excited 0^+ state as $\langle M_1 \rangle$, then, for states with $(J^\pi, T) = (0^+, 1)$,

$$\langle M_0 \rangle^2 = 2(1 - \delta_{IM}) \quad (3)$$

$$\langle M_1 \rangle^2 = 2\delta_{IM}^1 \quad (4)$$

where δ_{IM}^1 is essentially the admixture of the 0^+ ground state into the excited 0^+ state. The branching ratio, B_1 , to the latter is

$$B_1 \approx \frac{t_0}{t_1} = \frac{f_1}{f_0} \cdot \frac{f_0 t_0}{f_1 t_1} = \frac{f_1}{f_0} \cdot \frac{2 \delta_{IM}^1}{2(1 - \delta_{IM})} \approx \frac{f_1}{f_0} \delta_{IM}^1 \quad (5)$$

where subscripts 0 and 1 again indicate the ground state and excited 0^+ state, respectively.

We have searched for non-analogue $0^+ \rightarrow 0^+$ transitions in the decays of four superallowed β emitters: viz, $^{38\text{m}}\text{K}$, ^{46}V , ^{50}Mn and ^{54}Co . Samples of $^{38\text{m}}\text{K}$ were produced with (α, n) reactions and of the other three activities with (p, n) reactions, all on isotopically enriched targets. The experiments were performed at the TASC facility, with a helium-jet gas-transfer system used to convey activities from the target chamber to a low-background counting location. There the activity-loaded NaCl aerosol clusters were deposited on an aluminized tape and the collected samples were periodically moved to two detector stations in sequence. The collection time was determined by the removal and insertion of a paddle between the helium-jet nozzle and the tape.

A 68% HPGe detector was used to look for the characteristic β -delayed γ rays from excited 0^+ states in the daughter. Since the non-analogue transitions are very weak (ppm level) strong samples (MBq level) were required. Passive shielding installed in front of the detector crystal removed direct exposure to the high flux of energetic positrons from the dominant ground-state branch, but the resulting bremsstrahlung radiation was intense enough to obscure any weak γ -ray branches. To overcome this limitation, we positioned two thin plastic scintillators in front of the HPGe detector and on either side of the transport tape. All recorded γ rays were tagged with the status of positron events in the scintillators. If a γ ray was observed in coincidence with a positron only in the scintillator on the opposite side of the sample from the HPGe detector, it identified an event in which the positron emerged from the sample heading away from the HPGe detector; thus, no bremsstrahlung could have been

produced in the shielding. If, however, a positron was observed in each scintillator, it identified an event in which a positron had backscattered in the shielding and then traversed both scintillators; such events were vetoed. When the scintillator conditions were invoked, the level of continuous background in the HPGe spectrum was reduced by a factor of 400 compared to the singles result. This permitted the observation of β -delayed γ -ray branches down to the 1 ppm level.

Each sample was assayed in front of the HPGe detector for a few half-lives. The next tape movement brought it into the centre of a continuous-flow gas proportional counter where positron events were observed with nearly 100% efficiency and multiscaled. A decay-curve analysis yielded the total number of decays that took place from the activity of interest. Detailed descriptions of the helium-jet system and the counting arrangements have been published elsewhere [9,12].

The results we obtained on the four superallowed β emitters are given in Table 1. Portions of the corresponding, scintillator-gated γ -ray spectra are shown in Figure 1. With our excellent sensitivity to weak transitions, we observed not only non-analogue $0^+ \rightarrow 0^+$ transitions but also the first cases in these emitters of allowed Gamow-Teller (GT) β transitions to excited 1^+ states. The latter transitions are important because they have the effect of altering the accepted branching ratio for the corresponding superallowed branch. Some comments on each of the four cases we studied are given in the following paragraphs. A more detailed

description of all new spectroscopic information obtained in our studies will be published in a forthcoming paper [13].

^{38m}K . The energy of the first excited 0^+ state at 3 377 keV in ^{38}Ar , and its decay are well known [14]. No evidence for its population from ^{38m}K β decay was observed.

^{46}V . Clear evidence of a non-analogue decay branch to the known 0^+ state in ^{46}Ti at 2 611 keV [15] was found as well as the first observation of a weak (113 ppm) GT transition to a 1^+ state at 4 317 keV. We used both γ rays from the decay of the 0^+ state - one at 1722 keV ($0_1^+ \rightarrow 2_1^+$) and the other at 889 keV ($2_1^+ \rightarrow 0^+$) - to evaluate the strength of the non-analogue decay branch, bearing in mind that the GT transition contributes 50% of the intensity of the 889 keV transition.

^{50}Mn . Information on excited 0^+ states in the daughter nucleus, ^{50}Cr , is very imprecise. There is some evidence for five possible 0^+ states below 5 MeV excitation [16], but it comes from only a few reaction studies and the excitation energies were not well established. Furthermore, ^{50}Cr is close to the middle of the fp shell so the competing β decay of the isomeric state in ^{50}Mn has many branches, which give rise to many polluting γ -ray transitions.

We made detailed studies of samples containing a mixture of ^{50}Mn and ^{50m}Mn as well as samples containing only the longer-lived ^{50m}Mn . Several new β -

decay branches and γ -ray transitions were assigned to the decay of the isomeric state, among them a 3 045 keV γ ray. With these decays accounted for, we assign two new GT branches to the decay of ^{50}Mn . They populate 1^+ states at excitation energies of 3 628 keV and 4 998 keV, with branching ratios of 570 ppm and 6.8 ppm, respectively. We found only one other γ -ray transition that could possibly originate from the β decay of ^{50}Mn . Its energy is 3 044 keV and it could therefore be the γ -ray connecting the second known 0^+ state in ^{50}Cr ($3\,850 \pm 20$ keV) to the 783 keV 2^+ state but, as mentioned above, a γ ray of similar energy was assigned to the decay of ^{50m}Mn . The energy of the γ ray in the mixed spectrum is distinctly lower than its counterpart in the pure ^{50m}Mn spectrum, its intensity is greater when normalized to other γ rays from ^{50m}Mn and it has a shorter decay time. These three observations, all just at or outside the 1σ level, are consistent with the peak at 3 044 keV being a doublet, with one component arising from the decay of ^{50}Mn and the other one from ^{50m}Mn . We have therefore concluded that up to 60% of the 3044 keV γ -ray peak area in the mixed samples run can be due to a non-analogue decay branch of ^{50}Mn , and we treated this as an upper limit to the strength of that branch.

^{54}Co . Clear evidence for a non-analogue decay branch to the known 0^+ state at 2 561 keV in ^{54}Fe [17] was seen. No GT transitions were observed.

Table 2 shows the δ_{1M}^1 values derived with eq. 5 from the experimental non-analogue branches listed in Table 1. The values that we have calculated for δ_{1M}^1 using the THH model [7] are shown for comparison; also listed are the δ_{1M} values (effectively upper limits on δ_{1M}^1) calculated for both the THH and OB [8] model. In general, the THH model δ_{1M}^1 values are in reasonable agreement with the experimental values and in all cases δ_{1M}^1 (exp) < δ_{1M} (theory): i.e., the amount of the analogue state found by experiment mixed into an excited 0^+ state is less than the amount the calculations claim is mixed out of the ground state. For the OB model, this is not found to be the case. The calculations of both models for the ^{38}Mg , sd-shell case, are not severely tested by our data but, for the fp-shell cases of ^{46}V and ^{54}Co , the OB model consistently underpredicts the extent of isospin mixing, probably as a result of a too severe truncation of the shell-model space used in the fp shell [18].

Up until the present work, there was no reason to favour either the THH or the OB model, and averages of the two model calculations were used. With the THH model now preferred, the use of calculated values for δ_{1M} from this model alone result in a slight increase in the value of G_V' . More important, we have provided a sound basis for trusting the calculations of δ_{1M} . It should be noted that our conclusions on the merit of the two models with respect to their δ_{1M} predictions does not have any implications for their predictions of δ_{R0} , the other major charge-dependent correction.

The present work includes the first observation of three allowed GT transitions seen in competition with ground state superallowed $0^+ \rightarrow 0^+$ β decay branches. One of these transitions, in ^{50}Mn , was intense enough that the ft value for the superallowed branch has been changed significantly. Furthermore, the upper limits established for possible GT branches in the decays of ^{38}K and ^{54}Co are now far below the level at which they could affect the strength of the superallowed branch. Incorporating these results into the world data for $0^+ \rightarrow 0^+$ superallowed decays [1] we obtain $G_V' / (\hbar c)^3 = 1.15044 (59) \cdot 10^{-5} \text{ GeV}^{-2}$, with the unitarity sum (eq. 5) being 0.9983 (15).

In summary, a sensitive detection system has permitted us to observe (or set sensitive limits on) non-analogue $0^+ \rightarrow 0^+$ β transitions in the decays of four superallowed β emitters. The branching-ratio data shown in Table 1 permit direct tests of charge-dependent mixing models which indicate that the Towner-Hardy-Harvey model is in reasonable agreement with the experimental data for superallowed β emitters in the fp shell. With the effects of isospin mixing now established, another source of uncertainty has been removed from nuclear measurements of the weak vector coupling constant.

The present work also constitutes the first serious search for Gamow-Teller branches in the decays of the superallowed β emitters ^{38}K , ^{46}V , ^{50}Mn and ^{54}Co . All cases were probed to at least to the level of 50 ppm in branching ratio level and three GT transitions were found.

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TABLE 1 SUMMARY OF EXPERIMENTAL DATA

	Samples studied	Number of decays observed	Non-analogue transition		
			E_γ (keV)	Peak area	B_1 (ppm)
^{38}mK	63 000	$5.3 \cdot 10^9$	1210	<140	<19
^{46}V	50 000	$2.6 \cdot 10^{10}$	1722	263	39 (4)
^{50}Mn	119 000	$5.3 \cdot 10^{10}$	3044	212	<3 ^{a)}
^{54}Co	93 000	$9.7 \cdot 10^9$	1153	763	45 (6)

a) Peak assumed to be a doublet. See text.

TABLE 2 ISOSPIN MIXING CORRECTIONS

Nuclide	Exp. (%)	Theory (%)		OB δ_{IM}
	δ_{IM}^1	δ_{IM}^1	δ_{IM}	
^{38}mK	<0.28	0.096(2)	0.100(2)	0.11
^{46}V	0.053 (5)	0.046(5)	0.087(10)	0.01
^{50}Mn	<0.016	0.051(23)	0.068(30)	0.004
^{54}Co	0.035 (5)	0.037(8)	0.045(5)	0.005

FIGURE CAPTIONS

Portions of gated γ -ray spectra obtained following the β -decays of ^{38m}K , ^{46}V , ^{50}Mn and ^{54}Co . The position of the expected $0^+_1 \rightarrow 2^+$ γ ray is indicated with an arrow in each case. The other big γ -ray peaks are: the double-escape peak of the 2 168 keV γ ray from the β -decay of ^{38}K , the single-escape peak of the 3 628 keV γ ray from ^{50m}Mn β decay and the 1 130 keV γ ray from ^{54m}Co β decay.



