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High-precision Half-life And Branching Ratio Measurements For Superallowed β^+ Emitters At TRIUMF-ISAC

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High precision measurements of the ft values for superallowed Fermi β transitions between $J^\pi = 0^+$ isobaric analogue states allow for stringent tests of the electroweak interaction described by the Standard Model. These transitions provide an experimental probe of the Conserved-Vector-Current hypothesis, enable the most precise determination of the up-down (V_{ud}) element of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix, and allow one to set stringent limits on the existence of scalar currents in the weak interaction. An extensive program of superallowed branching-ratio and half-life measurements at TRIUMF's Isotope Separator and Accelerator (ISAC) facility has covered the full range of superallowed emitters, from the lightest case, ^{10}C, to the heaviest case for which precision data are currently available, ^{74}Rb. These experiments have been performed using a 4π continuous-flow gas proportional β counter, the 8π γ-ray spectrometer, and, most recently, the new high-efficiency GRIFFIN γ-ray spectrometer. In this paper, recent highlights from the superallowed Fermi β decay program at TRIUMF will be summarized, including high-precision half-life measurements for all three of the lightest superallowed emitters, ^{10}C, ^{14}O, and ^{18}Ne, with the greatest sensitivity to a potential weak scalar current contribution, as well as high-precision branching-ratio measurements for the heavy superallowed emitters ^{62}Ga and ^{74}Rb.

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1. Introduction

Precision measurements of the ft values for superallowed Fermi β decays between nuclear isobaric analogue states with spin $J^\pi = 0^+$ and isospin $T = 1$ provide fundamental tests of the electroweak interaction described by the Standard Model [1]. Several theoretical corrections must, however, be applied to the experimental ft values in order to account for radiative and isospin symmetry breaking (ISB) corrections [2]. These corrected-ft values ($\mathscr{F}t$) depend uniquely on the vector current of the weak interaction and confirm the conserved vector current (CVC) hypothesis to 1.2 parts in 10^4 [1]. The world average $\mathscr{F}t$, which is determined from the 14 most precisely measured ft values, also provides the most precise determination of the weak vector coupling constant, G_V. Together with muon decay measurements, these decays provide the most precise determination of the up-down (V_{ud}) element of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix, and in combination with V_{us} and V_{ub}, confirm the unitarity of the CKM matrix at the 0.06% level [1]. Many approaches to calculating the ISB correction in superallowed β decays have been discussed in the past decade [3, 4, 5, 6, 7, 8, 9, 10, 11], and precise experimental measurements of the ft values are essential to constrain the model-dependent systematic uncertainties.

The superallowed Fermi β decays also provide sensitive probes of beyond the Standard Model scenarios by placing stringent limits on the presence of scalar currents in the weak interaction. In the presence of a scalar current, the constancy of the $\mathscr{F}t$ values is removed by the addition of a term to the integrand of the β decay phase-space integral, f, of the form $(1 + b_F\gamma/W)$, where b_F is the Fierz interference term which is a constant that characterizes the strength of the scalar interaction [12], W is the total positron energy in electron rest mass units, and $\gamma = \sqrt{1-(\alpha Z)^2}$, where Z is the atomic number of the daughter nucleus and α is the fine structure constant [2]. Precise measurements of the low-Z superallowed emitters which have the lowest Q-value and thus largest values of $\langle W^{-1}\rangle$ are therefore of particular interest as they have the most sensitivity to a possible contribution from scalar currents and can be used to directly extract limits on b_F.

Experimentally, the ft values are determined via the measurement of three quantities: the total transition energy, Q_{EC}, the half-life, $T_{1/2}$, and the branching ratio between isobaric analogue states, B. Each of these quantities can be measured at TRIUMF's Isotope Separator and Accelerator (ISAC) facility at several different experimental stations which include: the TRIUMF Ion Trap for Atomic and Nuclear Science (TITAN) [13]; a 4π gas proportional β counter; the recently decommissioned 8π γ-ray spectrometer, a spherical array of 20 Compton-suppressed high purity germanium (HPGe) detectors [14, 15], which was used along with several ancillary detectors including the Zero-Degree Scintillator (ZDS), the Scintillating Electron-Positron Tagging Array (SCEPTAR) [16], and the Pentagonal Array for Conversion Electron Spectroscopy (PACES); and the recently commissioned high-efficiency Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei (GRIFFIN) detector, an array of 16 HPGe clover detectors, which can also be used in conjunction with ZDS, SCEPTAR, and PACES [14, 17, 18].

2. Half-life Measurements

Measurements of the ^{10}C half-life were motivated by the inconsistencies between the existing world-average half-life dataset [1]. The two most recent, and most precise, half-life measurements showed very poor agreement [19, 20] with a $\chi^2/\nu = 5.7$, resulting in a highly inflated uncertainty in the evaluated world-average data [1]. The disagreement between these two results had a major effect on the limit placed on b_F, by the entire world superallowed data set, shifting its central value by 0.5σ depending on which of the two half-life measurements was adopted in the $\mathscr{F}t$ calculation. Since the 718-keV excited state in ^{10}B is populated in 100% of ^{10}C β decays, the half-life was measured using both direct β counting and the measurement of the characteristic 718-keV γ-ray which is emitted following each β decay.

The γ-ray photopeak counting experiment was performed using the 8π spectrometer [21]. A sample γ singles energy spectrum is shown in Figure 1 with the corresponding γ gate shown in the inset. The data within the corresponding 718-keV photopeak was corrected for both dead-time and pile-up effects, as described in detail in Ref. [23], and were subsequently fit to an exponentially decaying function using a maximum-likelihood technique [23] yielding $T_{1/2}(^{10}\mathrm{C}) = 19.2969 \pm 0.0052$ s. Systematic effects were considered by grouping the data according to the different experimental running conditions and a conservative systematic uncertainty of ± 0.0052 s was assigned to account for the $\chi^2/\nu = 2.01$ obtained from the grouping of the data according to the different shaping times used, resulting in the final result of $T_{1/2}(^{10}\mathrm{C}) = 19.2969 \pm 0.0074$ s [21]. Additional rate dependent effects were considered by systematically removing leading channels in the decay curve and re-fitting the data, as shown in Figure 2a. No evidence for any such effects was observed.

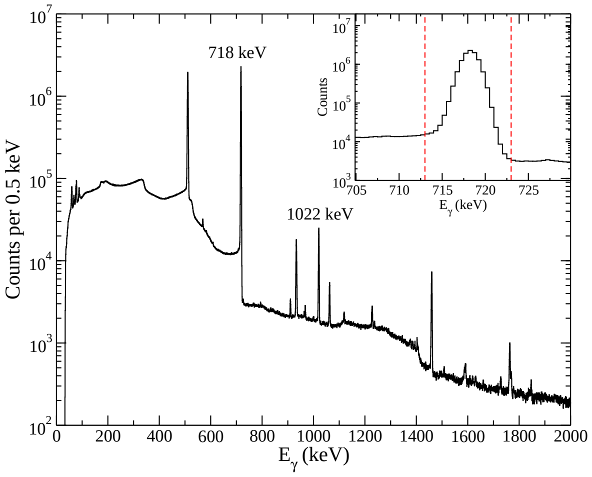

Figure 1: Sample γ-ray energy spectrum corresponding to the data taken with a 1 μs shaping time. The gate on the 718-keV γ-ray gate that was used to select events from the ^{10}C β decay is shown in the inset.

The β counting experiment was performed using 4π gas proportional counters which detect β particles with near 100% efficiency. The dead-time corrected data were fit and yielded a half-life of $T_{1/2}(^{10}\mathrm{C}) = 19.3009 \pm 0.0017$ s. An extensive set of systematics were considered, namely: two different gas counters, which are nearly identical except for the applied bias voltage needed to operate in the plateau region; applied bias voltages between $2400-2600$ V for the first gas counter, and $2700-2800$ V for the second counter; two different radioactive ion beams, a pure ^{10}C ($A = 10$) atomic beam as well as a ^{10}C^{16}O ($A = 26$) molecular beam; dwell times of 1.0 s, 1.2 s, and 1.4 s; and threshold voltages of 70 mV, 95 mV, and 120 mV [21]. No systematic biases from

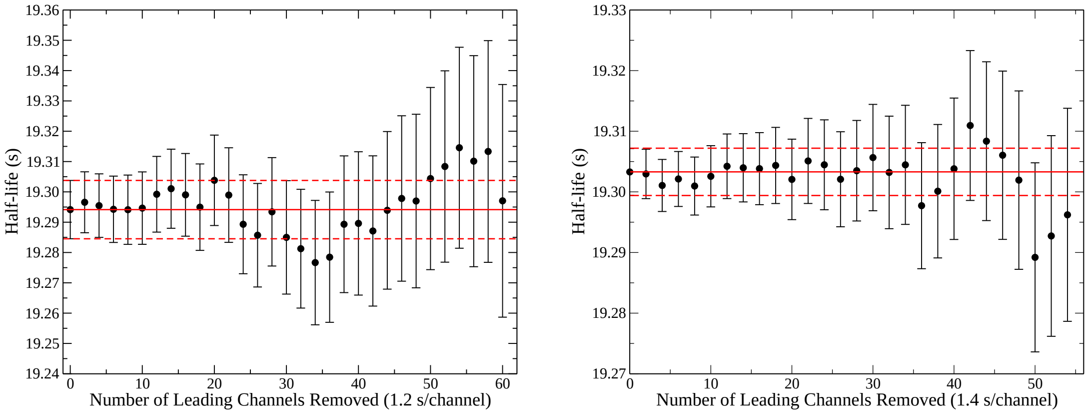

Figure 2: The half-life of ^{10}C with the removal of leading channels for (a) a subset of the γ-ray counting experimental data (corresponding to data taken with a 1.5 μs shaping time) and (b) a subset of the β counting experimental data (corresponding to data taken with a dwell time of 1.4 s). Since each data point contains all of the data to the right of it, the data are correlated and not expected to be scattered about the mean. No trend indicative of rate dependent effects are observed in either experiment.

these experimental running conditions were observed. Further investigation of rate dependent effects were considered by removing leading channels in the decay curve as shown in Figure 2b. No indication of any rate dependent effects were observed. Systematic corrections for uncertainties in the measured deadtimes and potential contaminants in the beam were also determined to be negligible, yielding a final half-life from the β counting experiment of $T_{1/2}$ (^{10}C) $=$ 19.3009 $\pm$ 0.0017 s. With a relative uncertainty of only $\pm$0.009%, this represents the most precise superallowed half-life measurement to date, surpassing an earlier measurement of the ^{26m}Al superallowed half-life measured to $\pm$0.012% [22], also performed at TRIUMF-ISAC.

The inclusion of the two half-life measurements in the ^{10}C dataset yields a new world-average half-life of $T_{1/2}$(^{10}C)= 19.3015 $\pm$ 0.0025 s, which represents an improvement in the uncertainty of the half-life by a factor of three compared to the previously adopted half-life [1]. Updating the evaluated superallowed data [1] with this new half-life measurement, as well as with recent ^{14}O Q-value [24] and branching ratio [25] measurements, a new limit of $b_F = -0.0018 \pm 0.0021$ is extracted from the 14 precisely measured $0^+ \rightarrow 0^+$ superallowed decays as shown in Figure 3.

Half-life measurements for ^{14}O, the second lightest $T = 1$ superallowed emitter, via simultaneous direct β counting and γ-ray photopeak counting, were also recently performed at the ISAC facility [26]. These measurements were motivated by an apparent systematic bias dependent on the method (β or γ counting) used to measure the half-life. Weighted averages of the half-life based on these two detection methods were inconsistent, quantified by a $\chi^2/\nu = 3.85$. The γ-ray photopeak experiment was performed with the 8π spectrometer [26]. Data was selected by gating on the characteristic 2312.6-keV γ-ray which is populated following ^{14}O β decay with a branching ratio of 99.4%. The data were corrected for pile-up and dead-time effects and a fit to the summed dataset yielded $T_{1/2}$(^{14}O)= 70.632 $\pm$ 0.077 s. The β counting measurement was performed using the ZDS plastic scintillator. The data were dead-time corrected and the fit to the data yielded $T_{1/2}$(^{14}O)= 70.610 $\pm$ 0.030 s. These two half-life measurements are consistent with one another

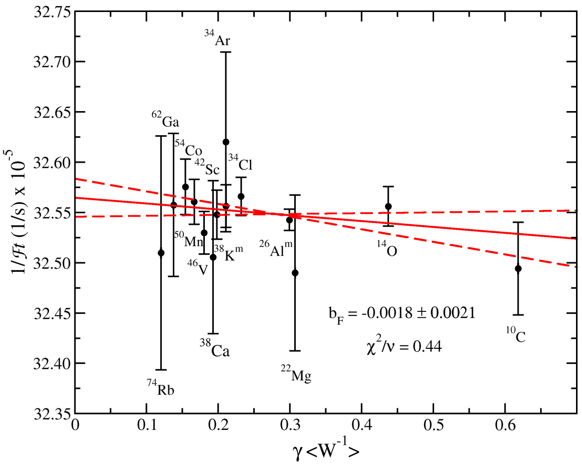

Figure 3: Plot of $1/\mathscr{F}t$ as a function of $\gamma\langle W^{-1}\rangle$ for the 14 precisely measured $0^+ \rightarrow 0^+$ superallowed transitions. The slope of the graph yields $b_F = -0.0018 \pm 0.0021$ which is consistent with the absence of scalar currents in the weak interaction.

and resolve the discrepancy between the different detection methods. Inclusion of these half-life measurements in the world average dataset results in the improvement of the ^{14}O half-life by a factor of 1.4 [26].

Recent measurements of the ^{18}Ne half-life were also performed at the ISAC facility [27]. Although ^{18}Ne is not currently one of the 14 precisely measured $\mathscr{F}t$ values used in the evaluation of the superallowed data [1], improvement in the precision of the ft-value for ^{18}Ne is motivated by its large model dependence on the ISB theoretical correction. In particular, evaluation of the ISB corrections in the most recent superallowed review by Towner and Hardy [1] which is calculated using radial wavefunctions with a Woods-Saxon potential constrained to measured binding energies and nuclear charge radii, in comparison to a previous evaluation by Towner and Hardy [3] which instead uses Hartree-Fock radial wavefunctions, show the largest disagreement for ^{18}Ne with a difference of 3.3σ [26] between the two ISB corrections. Improvement in the experimentally determined ft-value for ^{18}Ne can thus help to constrain the calculation of the ISB correction. The ^{18}Ne half-life was measured with two separate 4π gas proportional counters at TRIUMF-ISAC [26]. The half-life from the two experiments yield $T_{1/2}(^{18}\text{Ne}) = 1.66424^{+0.00072}_{-0.00064}$ s and $T_{1/2}(^{18}\text{Ne}) = 1.66368^{+0.00084}_{-0.00050}$ s, where the asymmetric uncertainties arise from the study of diffusion effects of the noble gas in the tape system [26]. The ^{18}Ne half-life is now determined to a precision of $\pm 0.034\%$ and awaits an improvement in the experimental precision of the Q-value and branching ratio in order to be included among the high-precision ft values.

3. Branching Ratio Measurements

Precise measurements of the ft values for the $A \geq 62$ superallowed β decays are important as these decays are predicted to have the largest ISB corrections due to their approximate dependence on Z^2. These transitions therefore provide a good opportunity to test the many different theoretical approaches used to calculate ISB corrections. Precise measurements of the branching ratios for these $A \geq 62$ decays are, however, complicated by the large Q-value and hence large number of competing Gamow-Teller β decay branches. The "Pandemonium" effect [28] leads to many weak γ-ray transitions which may be unobserved but collectively represent a significant fraction of the total non-superallowed β-decay intensity and thus hinder precision measurements of the branching ratio. Methods to address the Pandemonium effect have been developed by our collaboration and have been used in several analyses [29, 30, 31, 32]. A high-precision branching ratio measurement for the decay of ^{74}Rb was performed using the 8π spectrometer which measured the γ-rays, along with SCEPTAR and PACES for the measurement of β particles and β-delayed conversion electrons, respectively. In this experiment, the level scheme of ^{74}Kr was significantly expanded, with the placement of 23 excited states, in comparison to the 6 excited states previously measured [29], as well as the identification of 58 γ-ray and conversion electron transitions. The superallowed branching ratio was determined to be $B = 99.545(31)\%$ [32] which was an improvement by a factor of 3 relative to the previously measured ^{74}Rb superallowed branching ratio. This work also provided demanding, state-by-state, tests of the configuration mixing component of the ISB corrections through measurements of the weak non-analog Fermi β decay branches to 0^+ states in the ^{74}Kr daughter nucleus, indicating that the shell model spaces currently used for the superallowed ISB corrections have difficulty reproducing the wavefunctions of the 0^+ states in this region of strong deformation and shape-coexistence [33, 34].

In the superallowed decay of ^{62}Ga, the spin assignment of the 2342-keV excited state in the ^{62}Zn daughter requires further investigation after data from a recent experiment [35] suggests a 2^+ rather than 0^+ assignment. This change would lead to a change in the first 0^+ excited state from 2342-keV to 3042-keV, resulting in a significant ($\approx 50\%$) shift in the energy scaling used in the ISB correction. The new GRIFFIN [18] high-efficiency γ-ray spectrometer offers the opportunity to measure the spin and parity of the 2342-keV state via γ-γ angular correlations and a recent experiment was performed with GRIFFIN to study the ^{62}Ga superallowed decay at TRIUMF-ISAC. Analysis of the γ-γ angular correlation in order to resolve the spin assignment of the 2342-keV excited state, as well as detailed spectroscopy for the superallowed branching ratio measurement are currently in progress.

4. Summary

The intense radioactive ion beams and the suite of advanced detector systems available at the ISAC facility have enabled an extensive program of experiments that continue to push the limits of precision superallowed Fermi β decay measurements. Most recently, the half-lives of ^{10}C [21], ^{14}O [26], and ^{18}Ne [27], as well as the $0^+ \rightarrow 0^+$ superallowed branching ratio of ^{74}Rb [32] have been measured at the ISAC facility. Precise measurements of the ^{18}Ne half-life and ^{74}Rb branching ratio, as well as a new study of the ^{62}Ga branching ratio and γ-γ angular correlation measurement currently under analysis are important for constraining the many theoretical approaches used to calculate the isospin symmetry breaking corrections. The precise measurements of the superallowed ft values for the low-Z emitters are of particular importance as they are most sensitive to the presence of scalar currents in the weak interaction. The half-life measurements of ^{14}O have resolved a systematic discrepancy between β and γ-ray counting techniques which previously existed in the world-average half-life data and by doing so also led to an improvement in the precision of the adopted half-life by a factor of 1.4. The half-life measurements of ^{10}C have improved the consistency between the global ^{10}C half-life dataset which is important for setting an accurate limit on the contribution from weak scalar currents. Currently, the world-average superallowed $\mathscr{F}t$ values provides the most stringent limit on the Fierz interference term, $b_F = -0.0018 \pm 0.0021$ [21], which remains fully consistent with the absence of scalar currents in the weak interaction

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