

High-precision half-life and branching-ratio measurements for superallowed Fermi β^+ emitters at TRIUMF – ISAC

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Abstract. A program of high-precision half-life and branching-ratio measurements for superallowed Fermi β emitters is being carried out at TRIUMF's Isotope Separator and Accelerator (ISAC) radioactive ion beam facility. Recent half-life measurements for the superallowed decays of ^{14}O , ^{18}Ne , and $^{26}\text{Al}^m$, as well as branching-ratio measurements for $^{26}\text{Al}^m$ and ^{74}Rb are reported. These results provide demanding tests of the Standard Model and the theoretical isospin symmetry breaking (ISB) corrections in superallowed Fermi β decays.

1 Introduction

High-precision measurements of the β decay ft values for superallowed Fermi transitions between nuclear analog states of spin $J^\pi = 0^+$ and isospin $T = 1$ provide demanding, and fundamental, tests of the minimal electroweak Standard Model, including the conserved vector current (CVC) hypothesis and the $V - A$ form of the weak interaction [1, 2]. The superallowed β emitters, in combination

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with muon decay, currently provide the most precise determination of V_{ud} , by far the most precisely measured element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, and, when combined with V_{us} and V_{ub} , confirm CKM unitarity to a precision of $\pm 0.06\%$ [1, 2]. However, these fundamental tests require theoretical radiative and isospin symmetry breaking (ISB) corrections [3] to be applied to the experimentally measured ft values in order to obtain “corrected” ft values, denoted $\mathcal{F}t$; according to the CVC hypothesis, the $\mathcal{F}t$ values should be constant for all superallowed decays involving states of a given isospin T . The ISB corrections, in particular, have been the focus of many recent studies employing a wide range of theoretical and semi-empirical approaches [2–12], and significant differences are found between the various models. Testing these ISB corrections through high-precision experimental measurements is thus crucial.

A program at the Isotope Separator and Accelerator (ISAC) facility at TRIUMF, Canada’s national laboratory for particle and nuclear physics, is in place to perform high-precision half-life, branching-ratio, and Q value studies for these superallowed β emitters. These experiments are performed using TRIUMF’s Ion Trap for Atomic and Nuclear Science (TITAN) [13]; a 4π gas proportional β counter; and the 8π γ -ray Spectrometer [14], a spherical array consisting of 20 Compton-suppressed high-purity germanium (HPGe) detectors, with ancillary detection systems including the Zero-Degree Scintillator (ZDS), the Scintillating Electron-Positron Tagging Array (SCEPTAR), and the Pentagonal Array for Conversion Electron Spectroscopy (PACES) [15]. With the capability of measuring all experimental quantities required for determining superallowed ft values, ISAC is providing crucial data to help distinguish between the theoretical models used for calculating ISB corrections.

2 Results and Discussion

The ft values for the lightest superallowed β emitters, ^{10}C and ^{14}O , are most sensitive to scalar interactions and are thus crucial for setting upper limits on the existence of fundamental or induced scalar currents in β decay [16]. In both cases, the half-life can be measured either by direct β counting or by measuring the γ activity since, with a branching-ratio of $>99\%$, both decay to an excited state of their daughters, ^{10}B and ^{14}N , which then emit 718.4 and 2312.6 keV γ -rays, respectively [17, 18]. An apparent systematic effect associated with the detection method used for previous half-life measurements calls into question the *accuracy* of the current average $T_{1/2}$ values for both ^{10}C and ^{14}O ; resolving this issue motivated our ^{14}O half-life experiment that is described in Ref. [19]. A very recent half-life experiment for ^{10}C was completed at ISAC in fall 2013 and will further address the existing systematic discrepancy between the β and γ detection methods.

Among the 13 most precisely measured superallowed β decays, $^{26}\text{Al}^m$ has one of the smallest and most precisely quoted theoretical ISB corrections [3]. This value does, however, exhibit one of the largest discrepancies between the Woods-Saxon and Hartree-Fock radial overlap corrections of Ref. [2], motivating improved experimental precision to test this model dependence. The precision of the $^{26}\text{Al}^m$ superallowed ft value was limited by the $\pm 0.03\%$ precision of the world average half-life [2] prior to our recent studies at ISAC. Using a 4π gas-proportional β counter with a fast tape transport system and employing the dead-time correction and maximum likelihood fitting techniques described in Ref. [20], the $^{26}\text{Al}^m$ half-life has now been measured with a statistical precision of $\pm 0.007\%$ [21]. A detailed investigation of potential systematic effects in this measurement led to a final result of $T_{1/2} = 6346.54(46)_{\text{stat.}}(60)_{\text{sys.}}$ ms, a factor of 2.5 times more precise than the previous world average. Additionally, a measurement of the $^{26}\text{Al}^m$ superallowed branching-ratio with the 8π γ -ray spectrometer at ISAC led to an inclusive upper limit of 15 ppm at 90% confidence on the sum of all non-analog decay branches, resulting in a superallowed branching-ratio of $100.0000^{+0}_{-0.0015}\%$ [22]. These results lead to a superallowed ft value of 3037.53(61) s, the most precisely determined for any of the superallowed decays.

As the ISB corrections are approximately proportional to Z^2 , the largest corrections occur in the heaviest superallowed emitters; among those with a high-precision ft value, ^{74}Rb is the heaviest and has an ISB correction of $\delta_C = 1.63(31)\%$ [3]. This decay has been a major focus of the superallowed program at ISAC, including a high-precision half-life measurement with a 4π gas-proportional β counter [23], a recent mass measurement using high-charge state radioactive ions with the TITAN Penning trap [24], and a charge radius measurement via co-linear laser spectroscopy [25]. Most recently, the superallowed branching-ratio for ^{74}Rb decay has been measured with the 8π γ -ray spectrometer. A total of 57 γ -ray transitions, as well as the $E0$ conversion electron decay of the low-lying 0^+ state of ^{74}Kr at 509 keV were placed in the ^{74}Kr level scheme following ^{74}Rb decay [26]. These data, combined with the techniques developed in Refs. [27, 28], allowed the determination of the superallowed branching-ratio to a precision of $\pm 0.031\%$ [26], a factor of 3 more precise than the previous measurement [29]. State-by-state comparisons [26] of the calculated isospin mixing corrections associated with the low-lying 0^+ states in the daughter ^{74}Kr , however, suggest that the current shell-model calculations [30, 31] have difficulty describing the 0^+ states in this region of strong deformation, shape co-existence, and shape transitions [32–35].

Although the ft value for the superallowed decay of ^{18}Ne is not yet sufficiently precise to be included in the survey of the 13 highest precision cases [2], there is much interest in this case as the different theoretical descriptions of ISB for ^{18}Ne decay exhibit some of the largest differences for any of the superallowed emitters [36]. In anticipation of a high-precision branching-ratio measurement, a priority for several $T_z = -1$ emitters [37], high-resolution β delayed γ -ray spectroscopy was performed following the decay of ^{18}Ne and the half-life was determined to be $T_{1/2} = 1.6648(11)$ s [36]. This result provides important input towards future experiments that aim to improve the precision of the ^{18}Ne ft value to the level of $\pm 0.2\%$; the case of ^{18}Ne is particularly attractive as it potentially provides a means to investigate the role of nuclear deformation in the calculation of the ISB corrections.

2.1 Thick-Tape Transport System

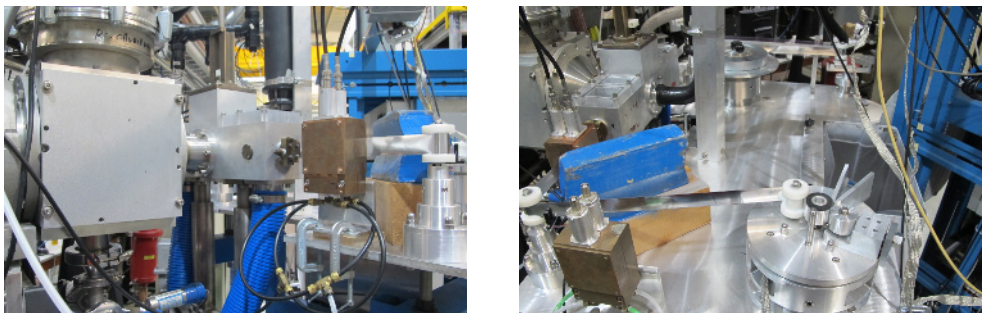


Figure 1. (Left) The 4π gas proportional β counter. The beam is implanted under vacuum, from the left, onto the tape system after which it is moved to the centre of the gas counter. **(Right)** An overhead picture of the new thick-tape transport system. The tape is fed counterclockwise from the spool at the top down to the disposal bin. Lead blocks have been added for additional shielding. A second, replica, gas counter was also recently commissioned and is pictured at the bottom.

Very recently, a newly commissioned thick-tape transport system, used in conjunction with the 4π gas proportional counter at ISAC, has been designed and commissioned for the measurement of half-lives of (noble) gaseous samples. The tape is 1/2 inch thick with a layer of 2.51 mg/cm² thick aluminum on

a mylar backing. The tape is controlled by a stepping motor and a magnetic brake to move samples from the implantation site to centre of the detector. A picture of the tape system is shown in Fig. 1. The tape system was commissioned with two experiments completed in the Fall of 2013 measuring the half-lives of the superallowed β emitters ^{18}Ne and ^{10}C using the methods described in Refs. [20, 21, 23]. The effect of diffusion from the tape was thoroughly investigated, and it was concluded that the gaseous samples were not susceptible to any effects on the time scale of the experiment.

The half-lives of two superallowed β emitters, ^{10}C and ^{18}Ne , have now been measured with this new experimental facility with statistical precisions better than 0.02% and 0.04%, respectively. These measurements, as well as simultaneous but independent measurements using the ZDS and 8π with comparable statistical precision, are more precise than any previous half-life experiments for these nuclei. Final analysis of systematic uncertainties in these measurements is currently in progress.

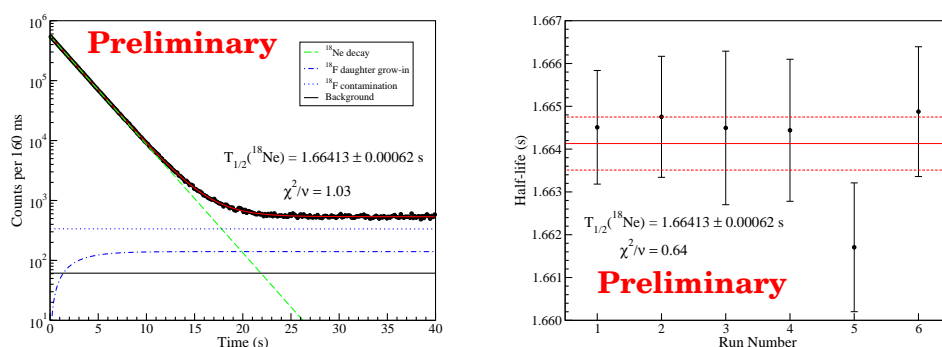


Figure 2. (Left) The sum of all data taken with the gas counter during the recent ^{18}Ne half-life experiment at TRIUMF. The data was first corrected for dead-time effects before being fit; the components of the fit are highlighted. (Right) Half-life versus run number and the weighted average that was performed on the data is shown; between runs experimental settings were varied to study their possible systematic effects.

3 Summary

The superallowed branching-ratios for $^{26}\text{Al}^m$ and ^{74}Rb decay, as well as the ^{14}O , ^{18}Ne , and $^{26}\text{Al}^m$ half-lives, have been measured to high precision at the TRIUMF-ISAC facility. The resulting $\mathcal{F}t$ values for these decays not only remain in excellent agreement with those of the other precisely measured superallowed emitters when using the Woods-Saxon radial overlap corrections of Ref. [3], supporting the accuracy of these calculations, but provide a rigorous test of the CVC hypothesis. For ^{74}Rb , the non-analog Fermi β branches to excited 0^+ states of the daughter nucleus [26] reinforce the need for expanded shell model spaces to accurately describe the 0^+ wavefunctions in the $A \geq 62$ region. The new high-precision experimental data for $^{26}\text{Al}^m$ serve to highlight the large impact that the model dependence of the ISB corrections for this case has on the world-average corrected $\mathcal{F}t$ value [21]. With an ongoing branching-ratio measurement and the high-precision half-life measurement performed at ISAC, ^{18}Ne may soon be included as one of the high-precision ft value cases and will help discriminate between theoretical models of ISB in superallowed decays. Finally, a high-precision half-life measurement for ^{10}C is being used to address a potential systematic discrepancy between β and γ -ray counting techniques.

Further high-precision superallowed β -decay data, as well as additional independent, first-principles, approaches to the ISB effects in these decays remain a priority of the community.

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