HIGH-PRECISION HALF-LIFE MEASUREMENT FOR THE SUPERALLOWED β^+ EMITTER ^{14}O

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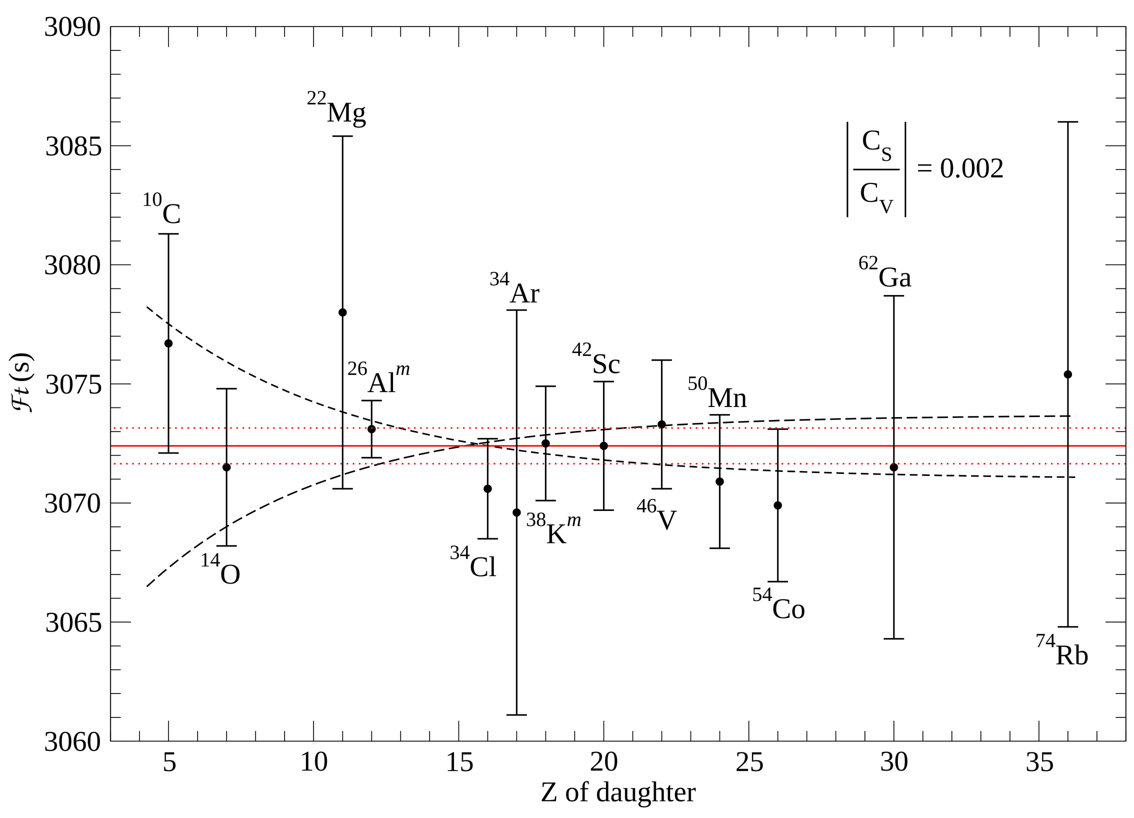
Motivation

In the Standard Model, the β decay Hamiltonian has the familiar $V - A$ form

$$\mathcal{H} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma_\mu(1-\gamma_5)\nu_e\bar{u}\gamma^\mu(1-\gamma_5)d] + \text{H.c.}$$

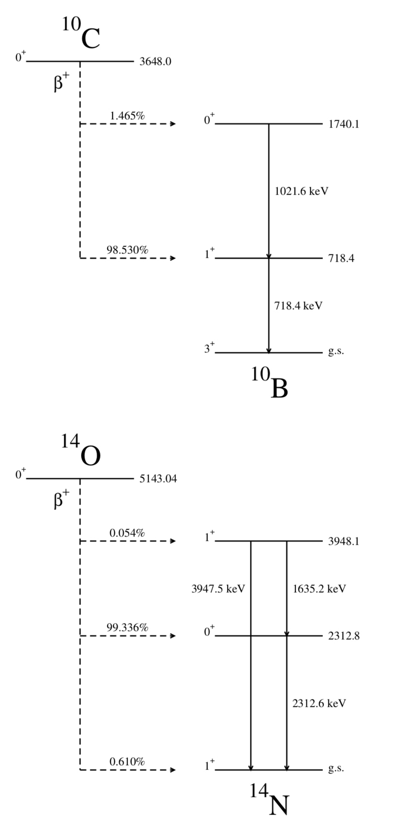
The most general form of the effective Hamiltonian describing β-decay includes other possible interaction types—scalar, pseudoscalar, and tensor contributions—for which only experimental upper limits have been set.

An invaluable probe of the Standard Model description of the electroweak interaction is provided by high-precision measurements of the ft values for superallowed Fermi β decays between 0^+ isobaric analog states. These decays have confirmed the conserved vector current (CVC) hypothesis at the level of two parts in 10^4 and currently provide the most precise value for the up-down matrix element, V_{ud}, of the Cabbibo-Kobayashi-Maskawa (CKM) quark mixing matrix [1]. After making theoretical QCD and QED corrections, corrected ft values, denoted $\mathcal{F}t$, are expected to be nucleus independent [2]. As ^{10}C and ^{14}O are the superallowed decays with the smallest Q-value (decay energy), they are particularly sensitive to the existence of a fundamental or induced scalar interaction in the weak interaction.



The corrected ft values for the 13 most precisely measured superallowed Fermi β emitters. Overlaid is the curvature of the corrected ft values for a scalar interaction of $\pm$0.02% of the vector interaction. Data from [1, 2, 4].

Half-Life Measurements by β & γ Counting



One of the most precisely measured superallowed half-lives known is that of ^{14}O. There are two primary methods for measuring superallowed decay half-lives. One method counts the gamma activity since, with a branching ratio of 99.4%, the ^{14}O decays to its daughter ^{14}N which then emits a 2.3 MeV γ-ray. The other method directly counts the β particles. An unsettling systematic effect arises when comparing the results from these two experimental methods. The photopeak counting ($T_{1/2}(\gamma)$ = 70.616(13) s) and the direct β counting experiments ($T_{1/2}(\beta)$ = 70.696(52) s) differ by 0.11%, or 1.3σ.

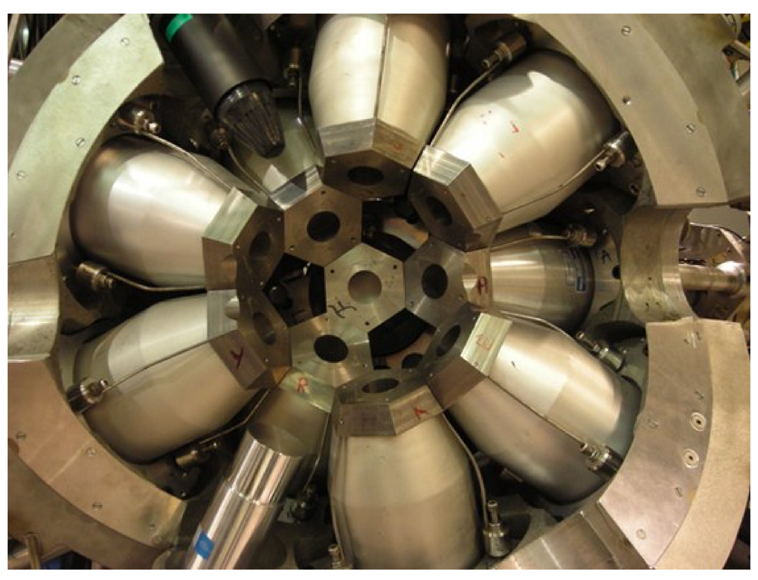
Of the three previous measurements of the ^{10}C half-life, there is also a discrepancy between the methods used. The single direct β counting experiment, although precise to a level of 0.02%, disagrees with the two gamma-ray experiments at a level of 2.6σ, or 0.13%.

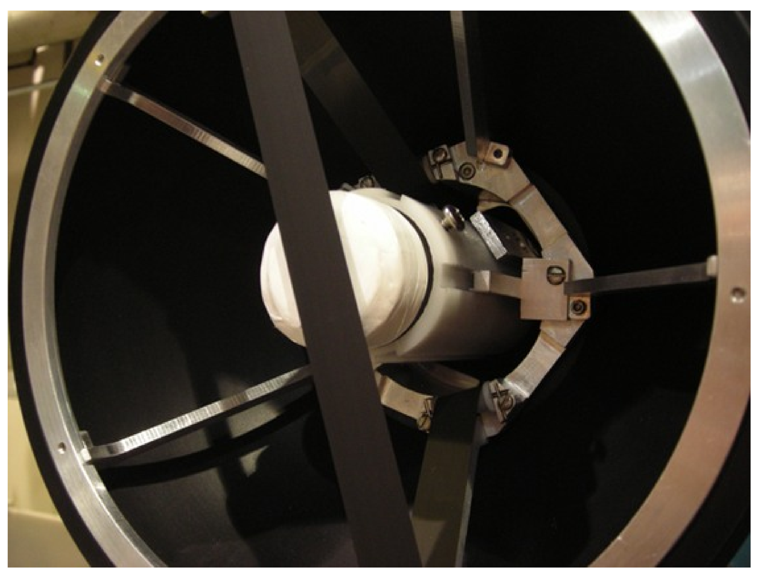
The low-Z superallowed decays are particularly important for the test of scalar currents, providing motivation for new simultaneous direct β and γ-ray counting experiments for these isotopes.

Experimental Overview

A simultaneous γ and β counting experiment for ^{14}O was performed at TRIUMF's Isotope Separator and Accelerator (ISAC) facility, where the primary driver is a 500 MeV cyclotron which provides intense beams of up to 100μA of protons. The detector set-up used for this measurement included the 8π Gamma-Ray Spectrometer, the Scintillating Electron-Positron Tagging Array (SCEPTAR), and a Zero-Degree Scintillator (ZDS). The beam was delivered as molecular carbon monoxide (^{12}C–^{14}O), and isobaric contaminants of ^{26}Na and ^{26}Al were also present. A total of 102 runs were performed where each consisted of 1 min. of background, 3 min. of beam on, and a 23 min. decay period.

The 8π γ-ray spectrometer is a spherically symmetric array consisting of 20 Compton-suppressed HPGe detectors covering approximately 13% of the 4π solid-angle to observe the gamma rays emitted from excited states in daughter nuclei. A series of ancillary detector systems—including SCEPTAR and the ZDS—can be placed within the array to provide information on the β particles. One of the hemispheres of 8π can be seen on the right.





Experiments are normally run in a cycling mode. Each cycle begins with the radioactive beam being implanted onto a tape at the centre of the detector arrays. The beam is then stopped and the decay of the sample recorded. When the species of interest has decayed away, the tape is moved to physically remove the daughter nuclei activities from sight of the detectors. The cycle then begins again. To the left, the tape is pictured with the Zero-Degree Scintillator behind it.

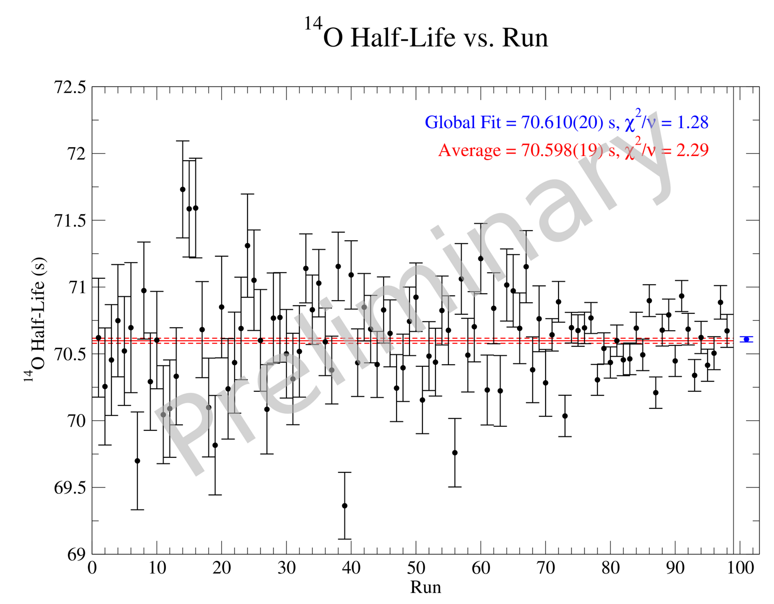
β Analysis

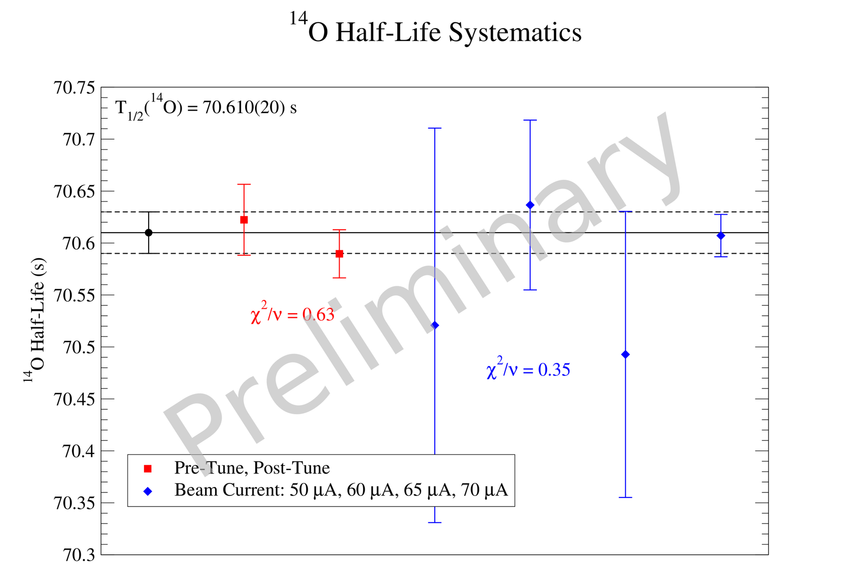
The β particles from the decay of the sample were registered independently using five multichannel scaler modules (MCS's) into 512 time bins of fixed width of 6 s. Fixed, nonextendable dead-times were applied to each MCS. These were chosen to be longer than the dead-times of the system and were measured to be 1.9818(36) μs, 5.0041(41) μs, 10.0042(38) μs, 20.0109(60) μs, and 29.9906(86) μs via the source-plus-pulser method. The data were corrected for dead-time effects then fit to extract the half-life of ^{14}O. The fit function, of five free parameters, consisted of three exponential decays—contaminants of ^{26}Na & ^{26}Al^m (with half-lives fixed at their central values of 1.07128 s [3] & 6.34654 s [4] respectively) and the ^{14}O—plus a constant background, which can be expressed as:

$$y_{fit}(t) = \int_{t_i}^{t_f} \underbrace{a_1 \exp\left(-\frac{\ln 2}{a_2}t\right)}_{^{14}\text{O}} + \underbrace{a_3 \exp\left(-\frac{\ln 2}{a_4}t\right)}_{^{26}\text{Na}} + \underbrace{a_5 \exp\left(-\frac{\ln 2}{a_6}t\right)}_{^{26}\text{Al}^m} + a_7 \, \mathrm{d}t\,.$$

To explore possible systematic effects, the deduced half-lives were grouped according to the various experimental settings, which can be seen below. To be conservative, we adopt the Particle Data Group's procedure of inflating the statistical uncertainty of our half-life measurement by $\sqrt{\chi^2/\nu} = 1.49$ for the largest χ^2/ν of these groupings (from the run-by-run averaging) to account for a possible systematic effect, equivalent to 0.023 s, associated with the experimental parameters.

$T_{1/2}(^{14}\text{O}) = 70.610(20)_{\text{stat.}}(23)_{\text{syst.}}$ s (Preliminary)

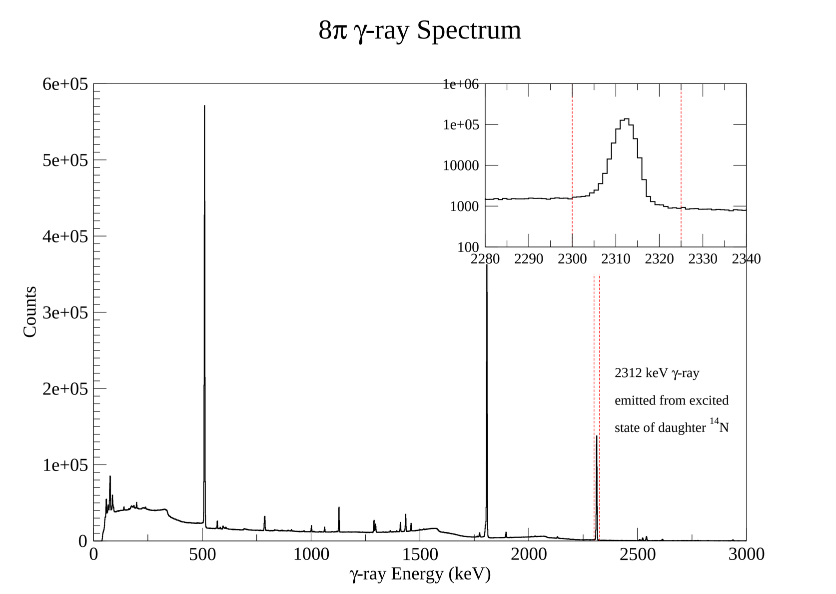




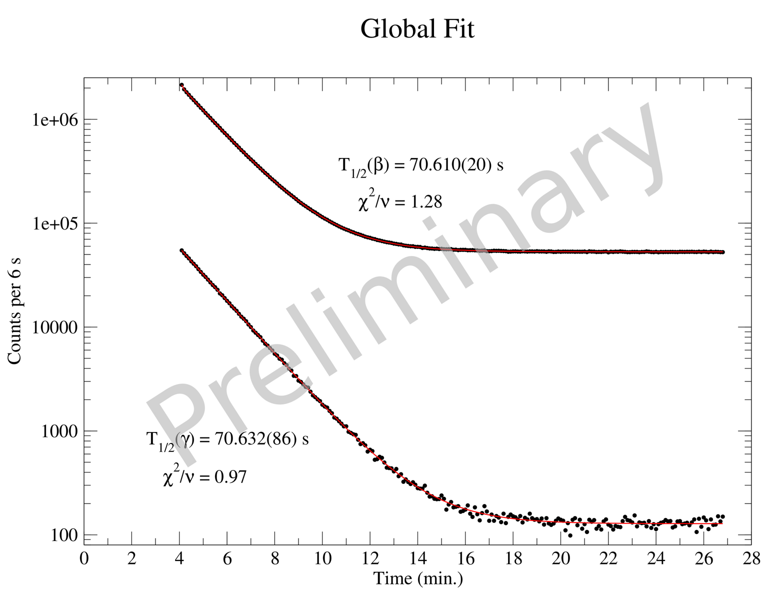
(Left) The deduced half-lives of each run using the data collected from the ZDS (β). (Right) An investigation of possible systematic effects caused by different run settings. It should be noted that the run-by-run averaging gives the largest χ^2/ν.

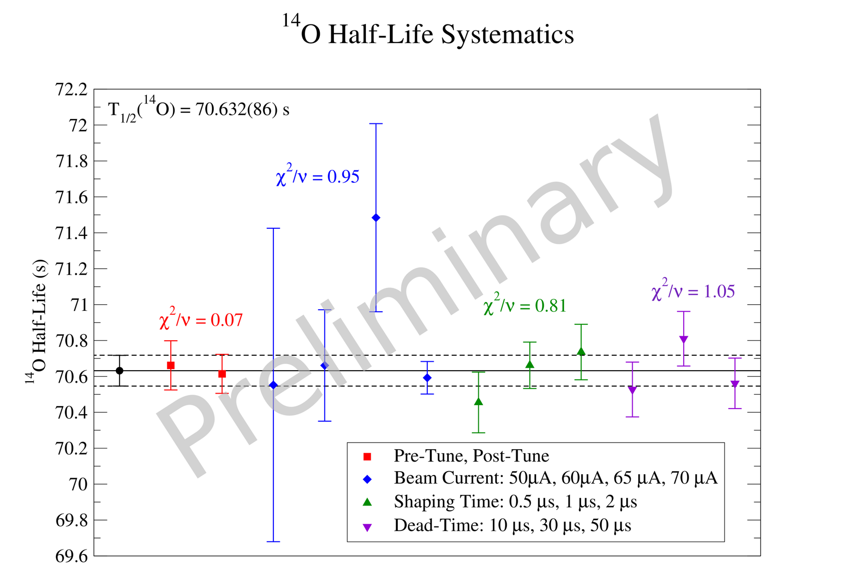
γ Analysis

The data were gated on the 2312.6 keV γ-ray and corrected for both dead-time and pile-up effects [5]. The same fit function was used with the exception that the intensity of ^{26}Al^m was set to zero as it does not produce γ radiation following its β decay and the bremsstrahlung contributions at 2.3 MeV in negligible. The same procedure for investigating systematic effects was performed as per the β analysis, and a preliminary result for the half-life has been found.



$T_{1/2}(^{14}\text{O}) = 70.632(86)_{\text{stat.}}(27)_{\text{syst.}}$ s (Preliminary)

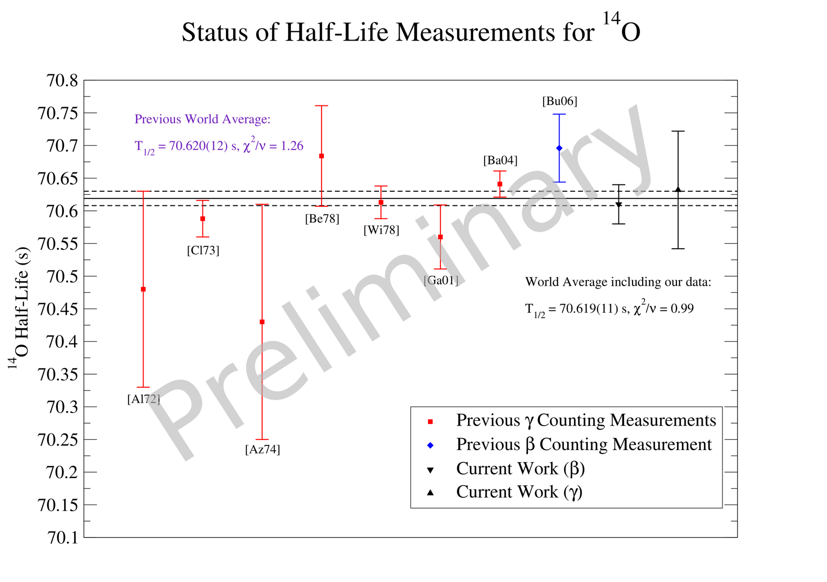




(Left) A comparison of the data, summed across all runs, for both the β and γ analyses. (Right) An investigation of possible systematic effects caused by different run settings. It should be noted that the run-by-run averaging gives the largest χ^2/ν.

Results & Conclusions

The use of the Zero Degree Scintillator for high-precision half-life measurements has been investigated. Preliminary half-lives of 70.632(90) s via γ counting and 70.610(30) s via β counting for ^{14}O are in excellent agreement with previous γ measurements. After obtaining high statistics from our follow-up experiments at both the 8π (via direct γ counting) and the General Purpose Station (via direct β counting) for both ^{10}C and ^{14}O we will be able to address the current systematic difference existing between the two experimental methods used, with important implications for limits on scalar weak interactions.



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