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A New Measurement of the Partial $0^+ \to 0^+$ Half Life of ^{10}C with GAMMASPHERE.

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We report on a new measurement of the strength of the superallowed $0^+ \to 0^+$ transition in the β-decay of ^{10}C: ^{10}C$(0^+, \mathrm{g.s.}) \to ^{10}B(0^+, 1.74\mathrm{MeV}) + \mathrm{e}^+ + \nu$. The experiment was done at the LBNL 88-inch cyclotron using forty seven GAMMASPHERE germanium detectors. Precise knowledge of this branching ratio is necessary to compute the superallowed Fermi ft, which gives the weak vector coupling constant and the u to d element of the Cabibbo-Kobayashi-Maskawa quark mixing matrix.

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The most precise value of the u to d element of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix is obtained from measurements of superallowed $0^+ \to 0^+$ Fermi β-decays in nuclear systems. Specifically, these decay rates determine the nucleon weak vector coupling constant G_V giving V_{ud}: $G_V^2 = G_F^2 |V_{ud}|^2 (1 + \Delta_R)$ where G_F is the Fermi coupling constant obtained from the muon lifetime and Δ_R is a nucleus independent ("inner") radiative correction. The conserved vector current (CVC) hypothesis implies that superallowed ft-values within isospin-1 multiplets are related to G_V by:

$$f(1 + \delta_R)(1 - \delta_C)\mathrm{t} \equiv \mathcal{F}\mathrm{t} = \frac{K}{G_V^2 |M_V|^2} \qquad (0.1)$$

where $|M_V|^2 = 2$ is the vector matrix element, f is the familiar Fermi statistical rate function, δ_R is the nucleus dependent ("outer") radiative correction, δ_C is the charge dependent correction to $|M_V|^2 = 2$ due to isospin symmetry breaking, and K is the usual β-decay constant. The corrected $\mathcal{F}$t include nuclear and radiative effects. Precise determination of G_V requires precision measurements of the partial $0^+ \to 0^+$ half-life, the β endpoint energy, and reliable theoretical calculations of δ_R and δ_C. Reference [1] summarized the status of measurements and calculations for ^{10}C, ^{14}O, ^{26}Al^m, ^{34}Cl, ^{38}K^m, ^{42}Sc, ^{46}V, ^{50}Mn, and ^{54}Co. The constancy of $\mathcal{F}$t for these nine precisely measured superallowed decays supports the CVC hypothesis. This review suggests $|V_{ud}| = 0.9740 \pm 0.0005$. Together with the two other elements in the first row of the CKM matrix taken from ref. [2], this tests the unitary of the CKM matrix. The result, $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \equiv |V|^2 = 0.9972 \pm 0.0013$, is more than two standard deviations from the unitary constraint.

A violation of CKM unitary requires the Standard Model to be extended. A more mundane explanation is unaccounted systematic uncertainties in the difficult theoretical calculations needed to extract V_{ud}. The calculation of the isospin symmetry breaking correction δ_C is regarded as the most problematic. Figure 1 shows the most precisely measured $\mathcal{F}$t as a function of daughter nucleus charge Z. Possible unaccounted Z-dependent corrections motivated extrapolations to zero charge using second and third order polynomials fits to δ_C-corrected [3] or uncorrected [4] ft values. The agreement of the extrapolated values with unitary suggests that incomplete isospin corrections might explain the discrepancy. The ft for the superallowed Fermi β decay of ^{10}C is of particular interest: ^{10}C has the lowest nuclear charge of a superallowed Fermi decay. Moreover, all existing calculations agree that δ_C for ^{10}C is small enough to be neglected.

The necessary experimental input are the total half-life, the branching fraction for ^{10}C$(0^+, \mathrm{g.s.}) \to$ ^{10}B$(0^+, 1.74\mathrm{MeV}) + \mathrm{e}^+ + \nu$, and the superallowed endpoint energy. The half-life (19.290 ± 0.012 seconds [5]) and the recently revised endpoint energy (885.86 ± 0.12 keV [6,7]) are known to high precision; the limiting experimental input is the $0^+ \to 0^+$ branching ratio. Figure 2 shows the ^{10}B and ^{10}C levels important for this measurement. The β decay of ^{10}C goes to the ^{10}B$(0^+, 1.740\mathrm{MeV})$ or the ^{10}B$(1^+, 0.718\mathrm{MeV})$ state. The allowed decay to the ^{10}B$(1^+, 2.154\mathrm{MeV})$ level is known to be small experimentally ($< 8 \times 10^{-6}$) as expected from the meager available energy. The forbidden β decay to the ^{10}B ground state is suppressed by about 10^{-10}. The decay to the ^{10}B$(0^+, 1.740\mathrm{MeV})$ state is followed with γ-rays at 1022 keV and 718 keV. The direct ground state decay of the ^{10}B$(0^+, 1.740\mathrm{MeV})$ level is magnetic octupole, with an estimated branch below 10^{-12} [8]. The decay to the ^{10}B$(1^+, 0.718\mathrm{MeV})$ state is followed by a single 718 keV γ-ray. Therefore the $0^+ \to 0^+$ branching ratio is the same as the γ-ray intensity ratio:

$$\mathrm{b} = \frac{\mathrm{I}_\gamma(1022\mathrm{keV})}{\mathrm{I}_\gamma(718\mathrm{keV})} = \frac{Y(1022\mathrm{keV})}{Y(718\mathrm{keV})} \frac{\epsilon(718\mathrm{keV})}{\epsilon(1022\mathrm{keV})} \qquad (0.2)$$

where $Y(\gamma)$ is the γ-ray yields from ^{10}C β-decay and $\epsilon(\gamma)$

full energy γ-ray detection efficiencies.

This experiment was performed with the GAMMAS-PHERE [9] detector at the Lawrence Berkeley National Laboratory 88-Inch Cyclotron. Three measurements are required: a measurement of the γ-ray yield ratio following β-decay, the full energy γ-ray detection efficiency ratio, and the 2×511 keV pileup background to the 1022 keV γ-ray peak. For the β-decay measurement, the ^{10}C source is produced with the ^{10}B(p, n)^{10}C reaction using a 325μg/cm^2 thick target of 99.5% enriched ^{10}B on a 600μg/cm^2 thick carbon backing and a 250 nA 8 MeV proton beam. The β delayed γ-rays from ^{10}C decay were detected by forty-seven GAMMASPHERE germanium detectors. The usual BGO Compton suppressors were turned off in order to avoid possible systematic effects from "false vetoes" by an unrelated γ-ray. A 35 second beam-on/beam-off cycle with a 1 second delay was used. We use a technique employed by a previous experiment [3] for measuring the γ-ray efficiency ratio. The efficiency is measured in situ with the γ-rays of interest by tagging γ cascades prepared by exciting the ^{10}B(1$^+$, 2.154MeV) state. A reduced intensity 10 nA proton beam is used to populate this state with ^{10}B(p, p')^{10}B*. The ^{10}B(1$^+$, 2.154MeV) $\rightarrow$ ^{10}B(0$^+$, 1.740MeV) transition is tagged with the 414 keV γ-ray. The ^{10}B(0$^+$, 1.740MeV) state then decays to the ^{10}B ground state by emitting exactly one 1022 keV γ-ray and one 718 keV γ-ray. The distribution of these γ-ray is isotropic because the cascade begins with the 0$^+$ state.

Figure 3a shows the β-delayed γ-ray energy spectrum. We use the following procedure to determine the γ-ray yields. The region around the γ-ray peak is fit to a function imitating the peak and a smooth underlying background. The peak is modeled by a Gaussian having small exponential tails and the background is taken as a quadratic polynomial with a resolution smoothed step function. The step function accounts for the discontinuity in the background caused by scattering of γ-rays in inactive material in front of the detector. Peaks for background radiation are included. The fit is performed by minimizing a Ξ-square function [10] using MINUIT [11]. The fitting procedure is used only for determining the background; the yields are computed by subtracting the fitted background from the data.

Figure 3b shows the γ-ray spectrum from the ^{10}B(p, p')^{10}B* reaction. The gating process is as follows. A fit to the 414 keV peak is performed using the method described. The result is used to determine the energy window, defined to be $\pm 1\sigma$ centered about the peak. The 414 keV peak is on a smooth background which includes Compton scattering of higher energy γ-rays. The effect of this Compton background is estimated by taking eleven additional energy gates below and twelve above the 414 keV peak. The Compton background is determined for each gate and a quadratic polynomial interpolation is used to estimate the Compton background under the 414 keV γ-ray peak. The background under the 414 keV peak also includes a small double escape peak from the 1436 keV γ-ray which is emitted in the ^{10}B(1$^+$, 2.154MeV) $\rightarrow$ ^{10}B(1$^+$, 0.718MeV) transition. Since the 1436 keV γ-ray is always emitted with a 718 keV γ-ray and never with a 1022 keV γ-ray, a small correction is applied to the efficiency ratio. This correction is determined from the number of counts in the single escape peak and the ratio of double to single escapes from an EGS4 [12] Monte Carlo simulation. The accidental $\gamma_{414} - \gamma$ coincidences were corrected for by subtracting counts obtained in non-coincident time gates. The accidental gates were normalized to the coincidence gate by taking advantage of the fact that it is impossible for two 718 keV γ-rays to be in true coincidence. The normalization factor is chosen such that the $\gamma_{718} - \gamma_{718}$ coincidences disappears in the subtracted spectrum.

Since the 1022 keV γ-ray is emitted during the slow down of the recoiling ^{10}B, a small correction is made to account for the kinematical change in solid angle and the Doppler energy shift. The overall correction is reduced because of the symmetry of GAMMASPHERE. The size of the correction was calculated with Monte Carlo integration using the differential ^{10}B(p, p')^{10}B* cross sections from ref. [13], the lifetimes and cascade branching ratios from ref. [14], and the stopping powers from ref. [15].

The number of background 2×511 keV pileup counts in the 1022 keV γ-ray peak is measured using ^{19}Ne as a source of positrons. The ^{19}Ne source is prepared in situ with the ^{19}F(p, n)^{19}Ne reaction by bombarding a 325μg/cm^2 thick PbF target on a 600μg/cm^2 thick carbon foil backing with a 100 nA 8 MeV proton beam. Like the ^{10}C decay measurement, a 35 second bombardment and counting cycle was used. The ^{19}Ne decay is similar to ^{10}C with a 17.239 ± 0.014 sec. half-life and a similar β endpoint energy (1705.38 ± 0.80 keV). The ^{19}Ne is a source of 511 keV annihilation γ-rays with no true 1022 keV γ-ray, and the entire peak at 1022 keV is due to pileup. In order to normalize the ^{19}Ne data to the ^{10}C data, we use the following technique. The GAMMASPHERE data stream contains a 1 MHz clock and the absolute time of each trigger is known to 1 μs. Using this information, we determine the number N (2×511) of 511 keV γ-rays within a 1 μs time bin that follow a 511 keV γ-ray with an arbitrary delay for each detector. Like the summing of two annihilation γ-rays this is a purely random process. Neglecting, for the moment, small dead time corrections (which are later corrected for), N $(2 \times 511) = (R_{511} \cdot T)(R_{511} \cdot \tau_{\text{bin}})$ where R_{511} is the rate of 511 keV γ-rays in a single detector, T is the counting time, and $\tau_{\text{bin}} = 1$ μs is the bin width. Similarly, the number of 2×511 keV pileup counts in the energy spectrum is given by: Y $(2 \times 511) = (R_{511} \cdot T)(R_{511} \cdot \tau_{\text{pu}})$ where τ_{pu} is the pileup rejection time in the GAMMASPHERE amplifiers. The rate independent ratio

$$\frac{\text{Y}\,(2 \times 511)}{\text{N}\,(2 \times 511)} = \frac{\tau_{\text{pu}}}{\tau_{\text{bin}}} \quad (0.3)$$

is used to compute the summing correction.

With the exception of the 2×511 keV pileup, random pileup does not effect the ratio in eqn. 0.2. However, the correlated pileup of γ-rays from a single cascade is a possible systematic effect. Specifically, both the 718 keV and 1022 keV γ-rays can deposit energy into the same detector, in effect removing counts from the full energy peaks. The effect cancels to first order in the efficiency ratio and an EGS4 [12] Monte Carlo simulation indicates that this effect is $-0.032(3)\%$. However, due to the smallness of the ^{10}C $0^+ \rightarrow 0^+$ branch, this effect is significant in the decay measurement. Only about 1.5% of the 718 keV γ-rays are emitted with a 1022 keV γ-ray, but all 1022 keV γ-rays come with a 718 keV γ-ray. Systematically, more 1022 keV γ-rays will be removed from the full energy peak. The pileup correction for a single detector is estimated by measuring coincidences between different detectors in the GAMMASPHERE array. Neglecting,for the moment, threshold corrections, small variations in detector sizes, and the small $\gamma - \gamma$ angular correlation, the pileup correction is equal to

$$f_{\text{PU}} = \frac{1 + \frac{\text{Y}(1022 \cdot \text{x})}{\text{Y}(1022)}}{1 + \frac{\text{Y}(718 \cdot \text{x})}{\text{Y}(718)}} \quad (0.4)$$

where $\text{Y}(\gamma)$ is the total γ-ray yield and $\text{Y}(\gamma \cdot \text{x})$ is the γ-ray yield when there is a coincident event in a second detector. The correction for detector size and $\gamma - \gamma$ angular correlation are straight forward. The detector size is simply scaled by Y(718keV). Since the transition ^{10}B$(0^+, 1.740\text{MeV}) \rightarrow {}^{10}B(1^+, 0.718\text{MeV})$ is pure M1 and the transition ^{10}B$(1^+, 0.718\text{MeV}) \rightarrow {}^{10}B(3^+, \text{g.s.})$ is primarily E2, the $\gamma - \gamma$ angular correlation is equal to: $\text{P}\,(\cos\theta) = 1 - 0.0714 \cdot \text{P}_2\,(\cos\theta)$ [16]. The correction for threshold is more problematic. GAMMASPHERE uses constant fraction discriminators (CFD) whose thresholds are not easily described. To avoid this problem, we enforce a software threshold at 417 keV, well above the CFD threshold. An EGS4 [12] Monte Carlo simulation of GAMMASPHERE is used to correct for the fraction of events below 417 keV.

The room background was measured for 17.5 hours after the run. No γ-rays were found in the region of 718 keV. However, a background γ-ray, with an energy of 1022.6 ± 0.4 keV, was observed. Based upon constraints on half-life, intensity, and associated γ-rays, the only possible source is the β decay of ^{120}Sb. This was probably produced through proton activation, ^{120}Sn$(\text{p}, \text{n})^{120}$Sb, of the aluminum alloy foil lining the inside of the GAMMA-SPHERE scattering chamber. In addition to a 1023 keV γ-ray, the β decay of ^{120}Sb emits a 197.3 keV γ-ray with nearly equal intensity. We use this 197.3 keV γ-ray to scale the background spectrum to the ^{10}C decay data in order to subtract the ^{120}Sb contamination.

The summary of all corrections are shown in table I. The strength of the ^{10}C superallowed $0^+ \rightarrow 0^+$ branch is determined to be

$$\text{b} = [1.4665 \pm 0.0038(\text{stat}) \pm 0.0006(\text{syst})] \times 10^{-2} \quad (0.5)$$

where the systematic error dominated by the uncertainty in the EGS4 threshold correction in the correlated pileup correction. A comparison with previous experiments is shown in table II. This result is about one standard deviation from the results of ref. [3]. Our result for b along with previous measurements of the β endpoint energy and the total lifetime gives ^{10}C $\mathcal{F}\text{t} = 3068.9 \pm 8.5$ sec. and $|\text{V}_{\text{ud}}| = 0.9745 \pm 0.0014$, using the usual radiative corrections and the isospin breaking corrections $\delta_{\text{C}} = 0.16(3)\%$ from ref. [1]. The unitary test is satisfied with data from this experiment, $|\text{V}|^2 = 0.9983 \pm 0.0029$, but the error is large. The present experiment seems to favor a Z dependence correction of ref. [4] but is statistics limited and a more precise experiment is necessary to help resolve the issue.

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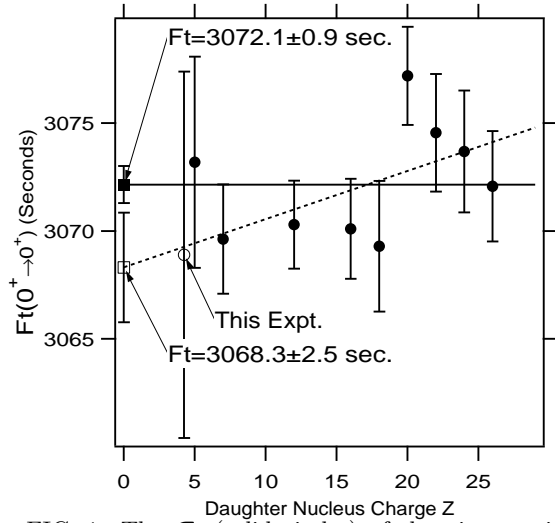[18] Y. Nagai, *et al.*, Phys. Rev. **C43**, R9 (1991).

FIG. 1. The $\mathcal{F}$t (solid circles) of the nine precisely measured superallowed decays (^{10}C, ^{14}O, ^{26}Al^m, ^{34}Cl, ^{38}K^m, ^{42}Sc, ^{46}V, ^{50}Mn, and ^{54}Co) plotted as a function of the daughter nucleus charge Z. The solid line is the weighted average. The dashed line is the result of a linear fit and the open square is the extrapolation of this fit to zero charge. The open circle is the ^{10}C $\mathcal{F}$t using the superallowed branching ratio from this measurement.

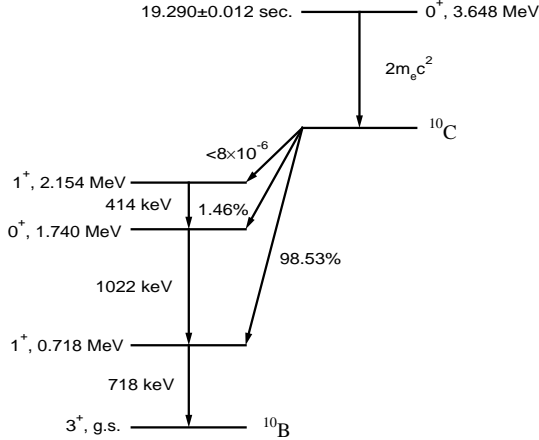FIG. 2. The relevant energy levels of ^{10}B and ^{10}C.
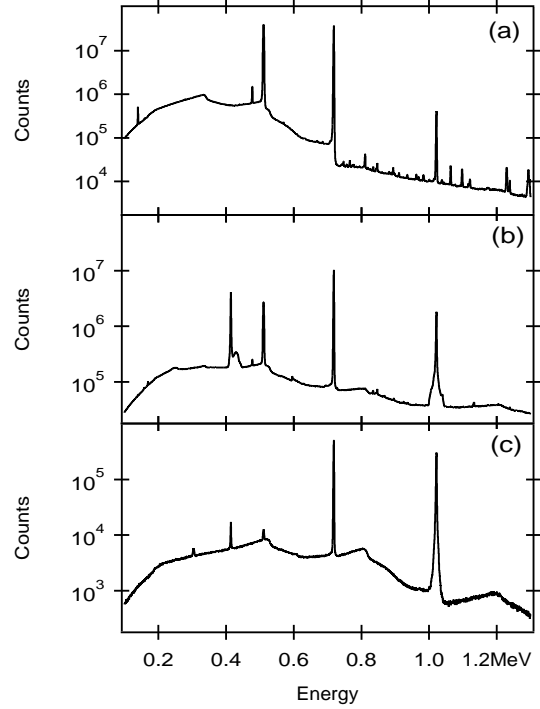

FIG. 3. (a) The β-delayed γ-ray energy spectrum. (b) The prompt γ-ray energy spectrum. (c) The prompt γ-ray energy spectrum gated by the 414 keV γ-ray. The peaks at 718 keV and 1022 keV in the delayed spectrum are from the β-decay of ^{10}C. The remaining peaks are due to positron annihilation, room background, neutron activation, and background proton reactions, primarily: ^{10}B(p, α)^{7}Be. The peaks at 718 keV and 1022 keV in the gated spectrum are used to measure the relative efficiency. The residual 414 keV γ-ray peak in (c) disappears after corrections are made for accidentals and Compton background.

TABLE I. Summary of the experimental corrections made in the measurement of the superallowed branching ratio.

Correction	Size	Affects
Accidental Coincidences	$-(1.94 \pm 0.02)\%$	Efficiency
Compton Background	$-(0.049 \pm 0.008)\%$	Efficiency
Double Escape Peak	$-(0.020 \pm 0.004)\%$	Efficiency
Kinematic Shift	$-(0.019 \pm 0.051)\%$	Efficiency
2×511 keV Pileup	$-(1.25 \pm 0.19)\%$	β-decay
Correlated Pileup	$-(0.032 \pm 0.003)\%$	Efficiency
	$+(0.44 \pm 0.05)\%$	β-decay
^{120}Sb Background	$-(0.23 \pm 0.11)\%$	β-decay

TABLE II. Comparison of ^{10}C superallowed $0^+ \rightarrow 0^+$ branching ratios.

Branching Ratio	Reference
$(1.465 \pm 0.014) \times 10^{-2}$	[17]
$(1.473 \pm 0.007) \times 10^{-2}$	[18]
$(1.465 \pm 0.009) \times 10^{-2}$	[8]
$(1.4625 \pm 0.0025) \times 10^{-2}$	[3]
$(1.4665 \pm 0.0038) \times 10^{-2}$	This work
$(1.4645 \pm 0.0019) \times 10^{-2}$	World Average