High-precision branching ratio measurement for the superallowed β^+ emitter ^{62}Ga

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A high-precision branching ratio measurement for the superallowed β^+ decay of ^{62}Ga was performed at the Isotope Separator and Accelerator (ISAC) radioactive ion beam facility. The 8π spectrometer, an array of 20 high-purity germanium detectors, was employed to detect the γ rays emitted following Gamow-Teller and nonanalog Fermi β^+ decays of ^{62}Ga, and the SCEPTAR plastic scintillator array was used to detect the emitted β particles. Thirty γ rays were identified following ^{62}Ga decay, establishing the superallowed branching ratio to be 99.858(8)%. Combined with the world-average half-life and a recent high-precision Q-value measurement for ^{62}Ga, this branching ratio yields an ft value of 3074.3 ± 1.1 s, making ^{62}Ga among the most precisely determined superallowed ft values. Comparison between the superallowed ft value determined in this work and the world-average corrected $\overline{\mathcal{F}t}$ value allows the large nuclear-structure-dependent correction for ^{62}Ga decay to be experimentally determined from the CVC hypothesis to better than 7% of its own value, the most precise experimental determination for any superallowed emitter. These results provide a benchmark for the refinement of the theoretical description of isospin-symmetry breaking in $A \geqslant 62$ superallowed decays.

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I. INTRODUCTION

Owing to their relative insensitivity to nuclear structure effects, superallowed Fermi β decays between 0^+ isobaric analog states offer a unique probe of the Standard Model description of electroweak interactions [1]. The conserved vector current (CVC) hypothesis, which states that the vector coupling constant G_V for semileptonic weak interactions is not renormalized in the nuclear medium, has, for example, been confirmed by the superallowed data to 1.3 parts in 10^4 [2]. Combined with the Fermi coupling constant G_F for purely leptonic decays, G_V from the superallowed data also currently provides the most precise determination [2] of $G_V/G_F = V_{\mathrm{ud}}$, the up-down element of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix. To date 13 superallowed ft values have been measured with better than $\pm 0.3\%$ precision and intense scrutiny has become focused on the corrections, of order $\sim 1\%$, that must be applied to the experimentally determined ft values to obtain the transition-independent $\mathcal{F}t$ values [1]:

$$\mathcal{F}t \equiv ft(1+\delta_R)(1-\delta_C) = \frac{K}{2\, {G_V}^2\, (1+\Delta_R)} = \text{ constant}, \tag{1}$$

where $K/(\hbar c)^6 = 2\pi^3\hbar \ln 2/(m_e c^2)^5 = (8120.278 \pm 0.004) \times 10^{-10}\,\mathrm{GeV}^{-4}$ s, δ_R is a nucleus-dependent radiative correction, Δ_R is a nucleus-independent radiative correction whose calculation involves both QED and hadronic QCD loop effects in the weak interaction process [3], and the nucleus-dependent isospin-symmetry-breaking correction δ_C corrects for Coulomb and charge-dependent nuclear forces that break the symmetry between neutrons and protons in the nucleus. To separate the nuclear-structure dependence, the nucleus-dependent radiative correction is split into two components [1],

$$\delta_R = \delta'_R + \delta_{\mathrm{NS}}, \tag{2}$$

of which the first, δ'_R, depends only on the end-point energy of the transition and the charge of the daughter nucleus Z and is therefore *independent* of nuclear structure whereas the second term, δ_{NS}, like δ_C, depends explicitly on nuclear structure. Grouping the corrections in terms of their nuclear-structure dependence yields [2]

$$\mathcal{F}t \equiv ft(1+\delta'_R)(1+\delta_{\mathrm{NS}}-\delta_C) = \frac{K}{2\, {G_V}^2 (1+\Delta_R)}. \tag{3}$$

The isospin-symmetry-breaking correction δ_C is also typically divided into two components, $\delta_C = \delta_{C1} + \delta_{C2}$ [2], where δ_{C2} accounts for the imperfect radial overlap of the spatial wave functions of the initial and final nucleons owing to differences in binding energy and the Coulomb potential experienced by the proton, and δ_{C1} accounts for different degrees of isospin mixing in the parent and daughter nuclear wave functions. This latter term is amenable to experimental verification. If

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isospin were an exact symmetry, ^{62}Ga Fermi β decay would exclusively populate the analog 0^+ ground state of ^{62}Zn. When the symmetry is broken there may be weak decay branches to excited nonanalog 0^+ states. If we express the Fermi matrix element squared to the nth nonanalog 0^+ state as $2\delta_{C1}^n$ and express the reduction in the analog transition Fermi matrix element squared as $2(1-\delta_{C1})$, then we have the approximate result [2]

$$\delta_{C1} \simeq \sum_n \delta_{C1}^n. \tag{4}$$

This result is exact when all the 0^+ states retained in the shell-model calculation have the same isospin, $T=1$ in this case. For those excited 0_n^+ states within the β-decay Q-value window, the δ_{C1}^n are measurable in principle [4] via the relation

$$\delta_{C1}^n \simeq \left(\frac{f_0}{f_n}\right) B_n, \tag{5}$$

where B_n is the β-decay branching ratio to the nth nonanalog 0^+ state, and f_n and f_0 are the phase-space integrals for the nth nonanalog 0^+ state and the ground-state analog transition, respectively.

Two groups [5,6] have made complete calculations of the isospin-symmetry-breaking corrections for the most precisely determined superallowed ft values. Both groups make use of shell-model calculations with the isospin nonconserving component of the interaction adjusted to reproduce coefficients of the isobaric multiplet mass equation (IMME) to determine the isospin-mixing component δ_{C1}. Towner and Hardy [5] use Woods-Saxon radial wave functions to obtain the radial-overlap correction δ_{C2}, whereas Ormand and Brown [6] derive this value from a self-consistent Hartree-Fock calculation. Although these two models exhibit similar nucleus-to-nucleus variations, the δ_C values calculated by Ormand and Brown have been systematically lower than those of Towner and Hardy, leading to a ± 0.9 s systematic uncertainty that is currently the dominant uncertainty in the world-average $\mathcal{F}t$ value [2] used to extract $V_{\rm ud}$ and test the unitarity of the CKM matrix. Furthermore, the recent inclusion of core orbitals in the calculations of Ref. [2] has led to significant changes in the adopted δ_C values for some superallowed decays and an overall 3.1σ reduction in the adopted value of $\overline{\mathcal{F}t}$. Experimental tests of the δ_C calculations are thus now more important than ever.

High-precision superallowed ft values in the $A \geqslant 62$ mass region provide an excellent opportunity to perform such tests, as the isospin-symmetry-breaking corrections are predicted to be large ($>1\%$) and strongly model dependent. In this work we report the results of a new high-statistics experiment that yields a superallowed branching ratio of 99.858(8)% for ^{62}Ga decay and also provides direct tests of the calculated δ_{C1}^1 and δ_{C1}^{2-3} for this decay. The present high-statistics results, which agree with and supersede our previous measurement [7] by the same techniques, represent the most precise branching ratio measurement for an $A \geqslant 62$ superallowed emitter and provide the strictest tests to date of the theoretical calculations of the large isospin-symmetry-breaking effects in these nuclei.

II. EXPERIMENT AND ANALYSIS

A. Experimental facilities and apparatus

The experiment was performed at TRIUMF's Isotope Separator and Accelerator (ISAC) facility in Vancouver, Canada. A 14.78 g/cm^2 ZrC production target was bombarded with 35-μA 500-MeV protons from the TRIUMF main cyclotron. The resulting spallation products were ionized by using the TRIUMF Resonant Ionization Laser Ion Source (TRILIS) [8] following their diffusion from the target surface. The TRILIS lasers were tuned to selectively ionize Ga isotopes and, following mass separation, yielded a secondary radioactive beam of $\sim$8000 ^{62}Ga ions/s. This yield was more than 20 times that from a conventional surface ion source utilized in a previous ^{62}Ga experiment at ISAC [9], and the ratio of ^{62}Ga to the primary isobaric contaminant ^{62}Cu was also improved by more than a factor of 20.

The ^{62}Ga ions were delivered as a low-energy (30-keV) 1^+ ion beam that was implanted onto a portion of a 13 mm wide and 50 μm thick continuous loop of aluminized Mylar tape, located at the mutual centers of an array of 20 thin (1.6-mm) plastic scintillators known as SCEPTAR [10,11] and the 8π γ-ray spectrometer [12], an array of 20 Compton-suppressed HPGe detectors. SCEPTAR detected the β^+ particles emitted in ^{62}Ga decay with $\approx$80% efficiency, while the 8π spectrometer was used to detect the γ rays emitted following Gamow-Teller and nonanalog Fermi β^+ decay branches. To minimize the effects of long-lived contaminants and daughter activities, the portion of tape containing the beam spot was moved out of the array at the end of every counting cycle to a vacuum chamber located approximately 1.5 m from the array and behind a 5-cm-thick lead wall.

The experiment was performed in a cycled mode defined by 4.1 s of background counting followed by 30.0 s during which the beam was implanted on the tape. The beam was then deflected at the mass separator by an electrostatic kicker while the decays from the beam constituents were counted for an additional 4.0 s before the sample was moved to the collector box outside the array and replaced with a fresh portion of tape to start a new cycle. The data acquisition remained on continuously during the experiment. The β information from SCEPTAR and the γ data from the 8π spectrometer were collected simultaneously, with each event given an absolute time stamp by latching scalers counting the pulses from a 10 MHz $\pm$ 0.1 Hz Stanford Research Systems SRS-SC10 temperature-stabilized precision oscillator. These scalers were reset at the start of each cycle and approximately 200 cycles were collected as an experimental "run." A total of 26 such runs were collected during the experiment.

B. Analysis of the SCEPTAR β data

SCEPTAR events were recorded in two parallel modes. A VME-based Struck SIS3801 multi-channel scalar (MCS) module was used to multi-scale the counts from each of the 20 individual SCEPTAR detectors, as well as from the full 20-detector array, in 100-ms bins. For those events that satisfied either a β-γ coincidence or scaled-down β-singles

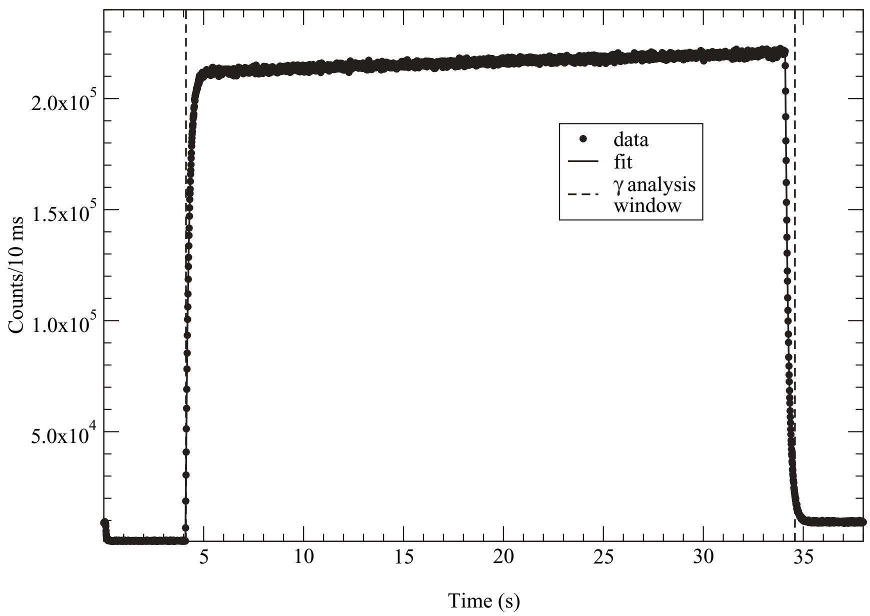

FIG. 1. Fit to the overall (summed) β activity from all 3975 good cycles in all runs. See text for details.

(scale down factor of 10) master trigger, full list-mode event data were recorded, including the integrated charge from the photomultiplier tubes and event times relative to the master trigger, in addition to the absolute time stamp recorded in 32 bits of a LeCroy 2367 universal logic module (ULM).

The MCS counts from all detectors were summed for each cycle to produce a counts-versus-cycle spectrum for each run. A lower limit threshold based on the average number of detected β particles per cycle was imposed to reject cycles during which the primary proton beam had tripped off or was still ramping up after having tripped off. The rejection of cycles during which the beam rate fluctuated was achieved by first summing the β activity curves from the cycles that remained following the imposition of the low-β-count threshold. This summed curve was fit by using a maximum likelihood algorithm [13] with the beam-on (t_{on}) and beam-length (t_{beam}) times as free parameters. Each cycle was then fit individually with t_{on} and t_{beam} fixed to the converged values from the sum fit and the beam intensity assumed constant. In this way, the χ^2/ν values from the fit to the β activity for each individual cycle became a good indicator of whether the beam had fluctuated significantly during the cycle. There were 4595 cycles recorded over the course of the entire experiment, of which 396 (8.6%) were rejected by the low-count threshold and 224 (4.9%) were rejected by the beam-fluctuation test.

To determine the total number of ^{62}Ga β^+ particles detected during the experiment, the MCS data were not used. The β-activity curve was rather reconstructed from the scaled-down list-mode data subjected to the same time conditions and scintillator pulse height thresholds used to establish β-γ coincidences for the subsequent γ-ray analysis. The total β-activity curve generated in this way and summed over all accepted cycles from all runs is shown in Fig. 1. This curve was fit with a maximum-likelihood procedure based on a Levenberg-Marquardt algorithm [13]. The fitting function included the time the beam turned on (t_{on}) and the beam-on duration (t_{beam}) as free parameters together with beam components of ^{62}Ga ($T_{1/2} = 116.121$ ms) [14] and its daughter ^{62}Zn ($T_{1/2} = 9.186$ hr) [15], ^{62}Cu ($T_{1/2} = 9.74$ min) [15], ^{62g}Co ($T_{1/2} = 90.0$ s) [15], and ^{62m}Co ($T_{1/2} = 13.91$ min) [15], in addition to a constant background. The half-life for each isotope was fixed at its known value and the fitting function also included the effects of electronic dead time in the SCEPTAR readout, which was a maximum of 1.2% at the peak of the β-activity curve. The ^{62}Ga, ^{62}Cu, and background intensities were treated as free parameters; analysis of the γ-ray data allowed the intensities of the contaminants ^{62g}Co and ^{62m}Co to be fixed at 0.091% and 0.55% of the ^{62}Cu intensity, respectively. The resulting fit to the SCEPTAR data is shown in Fig. 1 and yielded a total of $6.3355(6) \times 10^8$ ^{62}Ga β particles detected during the γ-ray analysis time window between cycle times of 4.12s (20ms after beam-on) and 34.58s (480ms after beam-off).

C. Analysis of the 8π γ-ray data

All γ rays detected with the 8π spectrometer, whether in singles or coincidence with a β particle detected in SCEPTAR, were recorded in list mode with γ-ray energies, event times relative to the trigger, and absolute time stamps recorded in an independent LeCroy 2367 ULM scaling the same 10 MHz $\pm$ 0.1 Hz oscillator signal as the β-stream ULM.

As can be seen in Fig. 2(a), even with $\approx$8000 ^{62}Ga ions/s the nonsuperallowed β branches of ^{62}Ga are sufficiently weak that the γ-ray singles spectrum is dominated by room background. By requiring a β-γ coincidence between SCEPTAR and the 8π spectrometer, these background transitions are essentially eliminated from the spectrum [Fig. 2(b)]. The overall background level is further reduced by suppressing the bremsstrahlung continuum that arises from the stopping of the energetic positrons from the ^{62}Ga superallowed decay ($Q_{\mathrm{EC}} = 9181.07 \pm 0.54$ keV) [16]. This suppression was performed during the offline analysis for β-γ coincidence

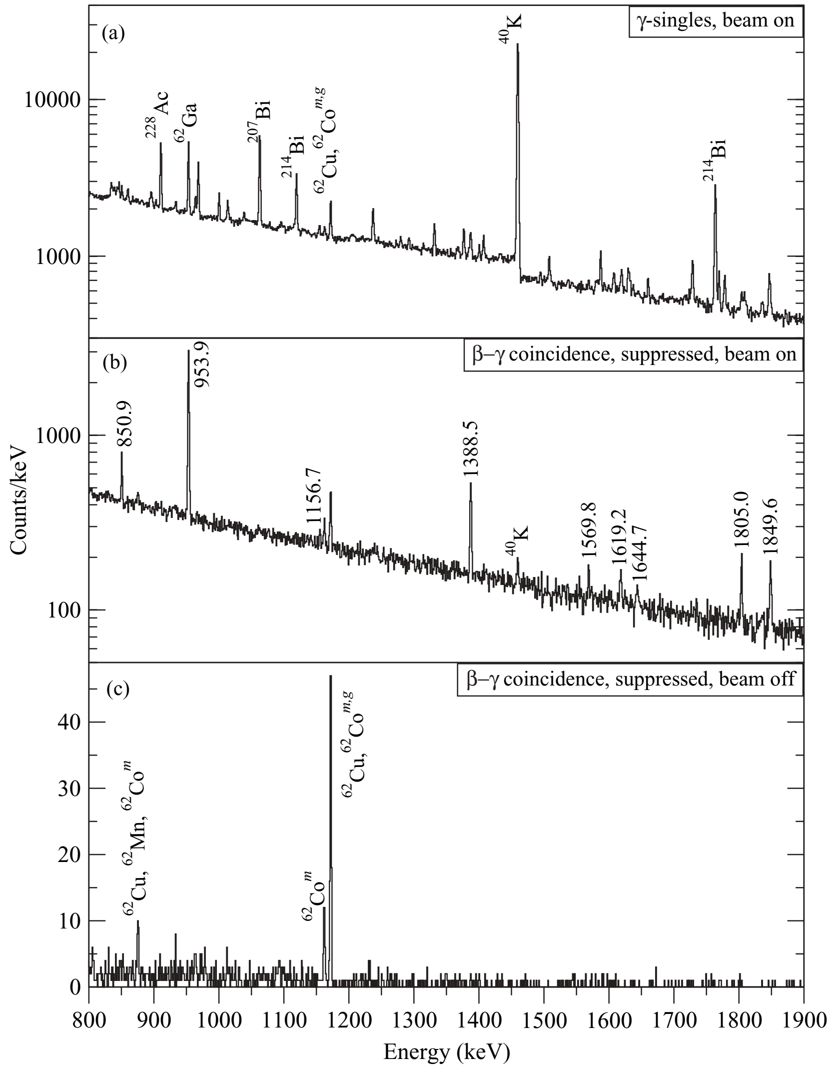

FIG. 2. Portions of the γ-ray singles (a) and β-γ coincident, bremsstrahlung-suppressed (b and c) spectra associated with the entire cycle (a), the beam-on portion of the cycle (b), and the beam-off portion of the cycle after the decay of ^{62}Ga (c). The last of these spectra was used to identify γ-ray transitions from in-beam contaminants.

events and was accomplished by vetoing any γ rays detected in the germanium crystal that is located immediately behind the scintillator paddle that detected the β particle, as this γ-ray detector is most likely to have been triggered by the resulting bremsstrahlung radiation. Transitions originating from long-lived in-beam contaminants were also identified [Fig. 2(c)] by gating on the beam-off portion of the β-activity curve from cycle times between 35.0 and 38.0s after the ^{62}Ga had decayed to a negligible level.

The bremsstrahlung-suppressed, β-coincident γ-ray spectrum (Fig. 3) was used to identify and determine the intensities of the γ rays emitted following ^{62}Ga β decay. For this analysis, the spectrum was taken within the same cycle time window used to determine the number of β particles (Fig. 1).

Efficiency data were collected prior to and immediately following the ^{62}Ga experiment. Decays from standard sealed sources of ^{152}Eu, ^{133}Ba, and ^{56}Co were measured over a period of several hours, providing a relative efficiency calibration to $E_\gamma \sim 3.2$ MeV. The decay of ^{62}Ga is, however, characterized by many transitions above 3.5 MeV. A beam of ^{66}Ga from ISAC was thus used as an additional relative efficiency calibration source, in conjunction with relative γ-ray intensities taken from the efficiency calibration work of Ref. [17]. The function $\ln(\epsilon) = \sum_{i=0}^{8} a_i (\ln E)^i$, where ε is the efficiency of the 8π array at γ-ray energy E (in MeV), was used to fit the relative efficiency curve as this function has been shown to accurately reproduce the γ-ray detection efficiency of germanium detectors over an energy range from 50 keV to 8.5 MeV [18]. Calibrated sources of ^{60}Co ($\pm 1.9\%$) and ^{137}Cs ($\pm 3.7\%$) were used to provide an overall normalization to the relative efficiency curve, yielding the absolute γ-ray detection efficiency of the 8π array shown in Fig. 4. The overall uncertainty in this absolute efficiency curve in the region 1–5 MeV was dominated by the uncertainty of the absolute calibration standards.

A correction was applied to the absolute efficiency to account for the fact that during the ^{62}Ga experiment the solid angle coverage of the 8π array was reduced by the vetoing of any germanium detector that was immediately behind a SCEPTAR detector hit by a β particle to avoid the inclusion of bremsstrahlung radiation in the γ-ray energy spectra. This correction factor is given by $C_{\rm Brem} = (20 - N_s)/20$, where N_s is the average number of SCEPTAR detectors registering a hit per event. This value was found to be 1.0634, giving a

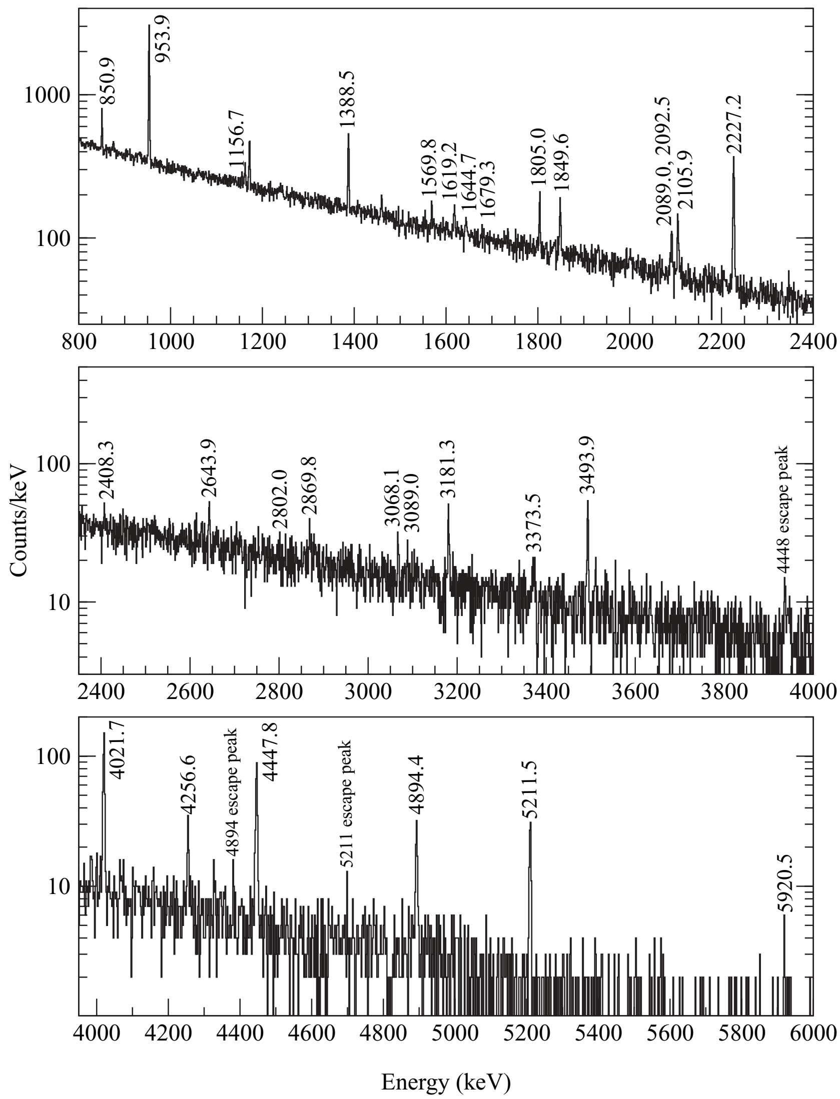

FIG. 3. Beam-on, β-γ coincident, bremsstrahlung-suppressed spectrum observed following the β^+ decay of ^{62}Ga. The γ-ray transitions assigned to ^{62}Zn are labeled by their energies in keV.

bremsstrahlung correction factor of 0.9468 to be applied to the absolute efficiency from the source data shown in Fig. 4. Because the β-γ angular correlation following an allowed β transition is isotropic, the bremsstrahlung correction factor is a constant and there are no angular correlation effects that would bias toward or against any particular branch in the β^+ decay of ^{62}Ga.

A total of 30 γ rays following the β^+ decay of ^{62}Ga were identified (Fig. 3). Their peak areas were efficiency corrected and divided by the total number of ^{62}Ga β^+ decays detected during the analysis window [$6.3355(6) \times 10^8$] to obtain the γ-ray intensities per ^{62}Ga β^+ decay shown in Table I. To investigate any potential β-detection bias associated with thresholds on the scintillator pulse height, simulations of the β particle energy deposited in SCEPTAR for the decay Q values associated with the excited states identified in this work were performed by using the GEANT4 [19] software simulation package. The ground state and 10 excited states at excitation energies 2342.4, 3181.2, 3374.4, 3961.0, 4021.8, 4448.2, 4895.2, 5211.6, and 5920.5 keV were simulated with approximately one-million β decays for each branch. The results of these simulations are shown in Fig. 5 and indicate that the experimental scintillator pulse-height thresholds, which were set below an equivalent deposited energy of 100 keV, introduced no significant bias in the β-detection efficiency between any of the decay branches identified in this work.

III. RESULTS

Prior to the current high-statistics experiment, the most detailed study of ^{62}Ga decay was carried out in a previous experiment [7] by our collaboration with the 8π spectrometer and SCEPTAR at ISAC. Compared to this earlier work we have identified 11 new γ-ray transitions with energies of 1032.0(5), 1156.7(4), 1569.8(4), 1619.2(4), 1679.3(6), 2089.0(8), 2408.3(7), 2802.0(12), 3089.0(10), 3373.5(8), and 5920.5(17) keV based on analysis of γ-ray singles (Fig. 3) and γ-γ coincidence spectra (Fig. 6). All 30 γ rays identified in this work have been placed in the ^{62}Zn level scheme (Fig. 7) based on energy sums and differences, and all expected γ-γ coincidences involving transitions having intensities above

TABLE I. Level and γ-ray energies in ^{62}Zn and their observed intensities per ^{62}Ga β decay. The final column represents the sum of direct β plus unobserved γ-ray feeding to each level.

J_i^π	E_i (keV)	E_γ (keV)	I_γ (ppm)	$I_{out} - I_{in}$ (ppm)
(1_7^+)	5920.5(17)	5920.5(17)	8(4)	8(4)
(1_6^+)	5211.6(4)	5211.5(11)	51(6)	110(10)
		4256.6(9)	29(4)	
		2869.8(7)	17(4)	
		2408.3(7)	13(4)	
(1_5^+)	4895.2(5)	4894.4(10)	42(5)	99(9)
		3089.0(10)	9(4)	
		2092.5(4)	47(6)	
(1_4^+)	4448.24(28)	4447.8(9)	109(8)	275(14)
		3493.9(7)	58(6)	
		2643.9(6)	26(5)	
		2105.9(4)	61(6)	
		1644.7(5)	21(5)	
(1_3^+)	4021.8(5)	4021.7(8)	149(10)	173(11)
		3068.1(8)	16(4)	
		1679.3(6)	8(5)	
(1_2^+)	3961.0(4)	1619.2(4)	35(5)	55(7)
		1156.7(4)	19(5)	
$(1^\pm, 2_4^+)$	3374.4(4)	3373.5(8)	18(4)	54(8)
		1569.8(4)	30(5)	
		1032.0(5)	6(5)	
(1_1^+)	3181.2(4)	3181.3(6)	42(5)	304(12)
		2227.2(4)	262(11)	
(0_{2-3}^+)	3042.9(8)	2089.0(8)	12(5)	12(5)
2_3^+	2803.5(4)	2802.0(12)	6(4)	−21(12)
		1849.6(4)	72(6)	
0_1^+	2342.45(33)	1388.5(3)	191(8)	64(14)
2_2^+	1804.88(20)	1805.0(4)	70(6)	105(12)
		850.9(2)	100(7)	
2_1^+	953.92(17)	953.9(2)	850(19)	122(27)[a]

[a]This value does not include a contribution from the decay of the tentative 0_{2-3}^+ state.

20 ppm were confirmed through analysis of the γ-γ coincidence data. An example of such γ-γ coincidence data with a gate on the 953.9-keV $2_1^+ \rightarrow 0^+$ transition is shown in Fig. 6.

A level at 3374.4(4) keV has been identified in ^{62}Zn by a ground-state transition of 3373.5(8) keV, a 1569.8(4)-keV transition to the 2_2^+ level at excitation energy 1804.9(2) keV, and a 1032.0(3)-keV transition to the 0_1^+ level at excitation energy 2342.45(33) keV identified in coincidence with the subsequent γ decay of the 0_1^+ by the 1388.5-keV γ ray. A previous measurement of the energy level structure in ^{62}Zn through ^{64}Zn$(p,t)^{62}$Zn reactions identified a level at an excitation energy of 3.35(2) MeV [20], tentatively assigned $I^\pi = 1^-$ or $I^\pi = 2^+$. This is possibly the same level identified here, in which case its feeding would result from the γ decay of higher lying 1^+ states fed in Gamow-Teller β decays of ^{62}Ga. We cannot, however, exclude the possibility that this is a new (1^+) state fed directly in ^{62}Ga β decay. We thus consider all of $(1^\pm, 2^+)$ for the assignment of this level.

A new level is identified at an excitation energy of 3961.0(4) keV, which decays to the 2803.5(4)-keV 2_3^+ and 2342.4(3)-keV 0_1^+ levels via the emission of 1619.2(4)- and 1156.7(4)-keV γ rays, respectively. Since these transitions feed 2^+ and 0^+ levels, the 3961.0(4)-keV level is tentatively assigned a spin-parity of 1^+ based on its apparent direct population in β decay of the $I^\pi = 0^+$ parent ^{62}Ga.

We also identify a γ-ray peak at 5920.5(17) keV following ^{62}Ga β decay. We note that in the γ-ray singles spectrum, several high-energy transitions originating from neutron capture on ^{56}Fe are identified, and ^{56}Fe capture produces a 5921-keV γ ray [21]. These ^{56}Fe neutron-capture peaks are absent in the β-γ coincidence spectrum, whereas the 5920.5(17)-keV peak clearly remains (Fig. 3), indicating the presence of this transition in ^{62}Ga decay. The 5920.5(17)-keV γ ray most likely represents a transition to the ground state of ^{62}Zn from an excited 1^+ level, but with no other identified γ decays to or from the proposed 5920-keV level its inclusion in the level scheme remains tentative.

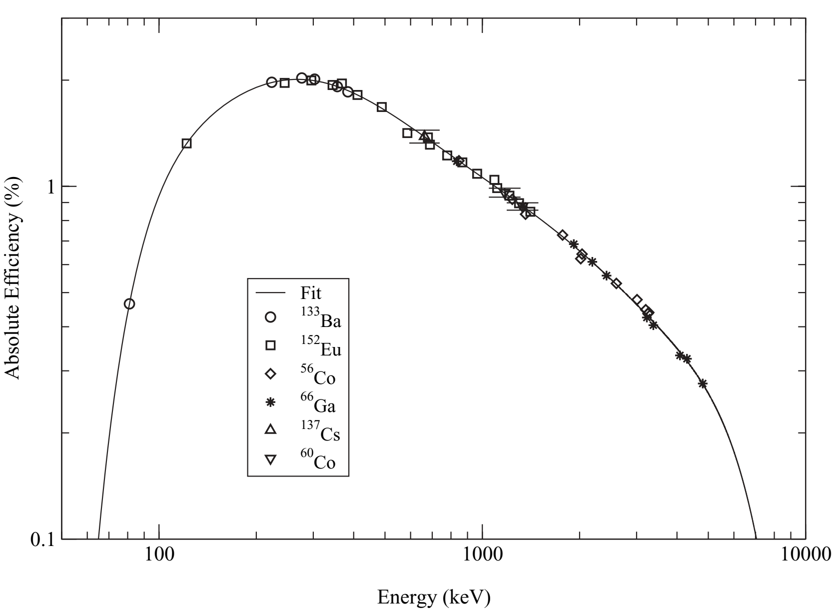

FIG. 4. Absolute efficiency curve for the 8π spectrometer. Uncertainties are shown for the ^{60}Co and ^{137}Cs calibrated sources used to convert the relative efficiency to an absolute value. The absolute efficiency at 1 MeV was determined to be 1.061(18)% in this experiment.

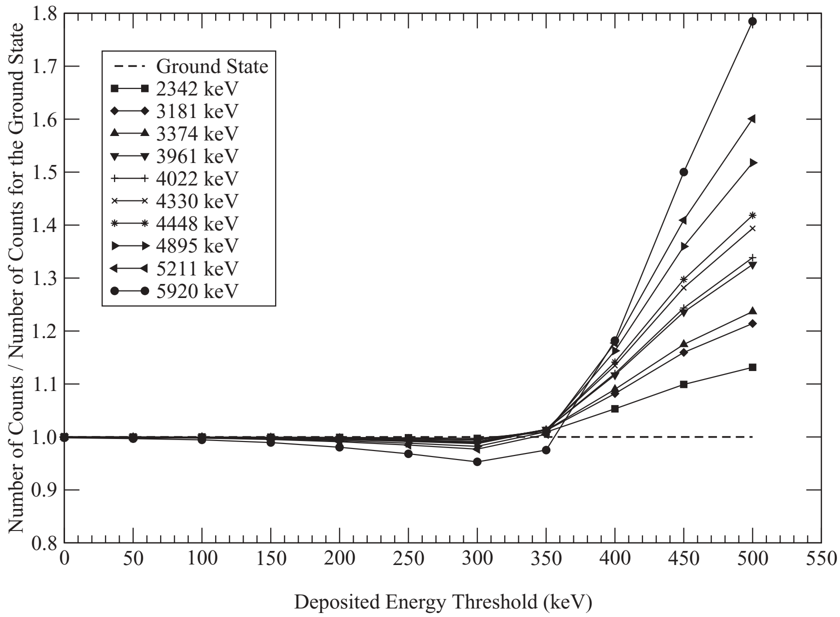

FIG. 5. GEANT4 simulation of the number of detected counts vs SCEPTAR deposited-energy threshold for each of the simulated β^+ branches in ^{62}Ga decay, normalized to the number of counts detected for the ground-state transition. The deposited energy threshold in the current experiment was below 100 keV, resulting in no significant bias in the β-detection efficiency between branches.

The remaining γ ray assigned to ^{62}Ga decay was at 2089.0(8) keV, and it could not be placed definitively in the decay scheme. We note that the shell-model calculation discussed in the following predicts a large nonanalog Fermi branch to the third excited 0^+ state in ^{62}Zn calculated at 3.05 MeV. This state is predicted to γ decay with a 99.6% branch to the first excited 2^+ state via a 2.10-MeV γ ray. The 2089.0-keV γ ray observed in this work is therefore a possible candidate for this decay, and we have tentatively placed an excited 0^+ state in ^{62}Zn at an excitation energy of 3042.9 keV. We further note that a ^{64}Zn$(p,t)^{62}$Zn reaction study [20] identified a level in ^{62}Zn at 3.06(1) MeV that was assigned as $I^\pi = 2^+$. However, careful inspection of the triton energy spectrum in Fig. 1 of Ref. [20] reveals a shoulder on the side of the 3.06-MeV peak, possibly indicating a level at approximately 3.04 MeV. The angular distribution for this doublet also shows significant intensity at 0°, consistent with a combination of 0^+ and 2^+ contributions. Although speculative, these data provide additional corroborating evidence for our tentative assignment of a 0^+ level at 3042.9 keV in ^{62}Zn (Fig. 7).

With the observed γ-ray transitions placed in the level scheme, the superallowed branching ratio is determined by subtracting the total γ-ray intensity feeding the ground state from unity. From column 4 of Table I, which gives the intensities (in parts per million) of all the γ rays identified in this experiment, the observed γ intensity feeding the ground state amounts to $I_{gs} = 0.1338(26)\%$. However, ^{62}Zn is predicted to have over 100 excited 1^+ states accessible via β^+/EC decay of ^{62}Ga [22]. The weak β feeding of these

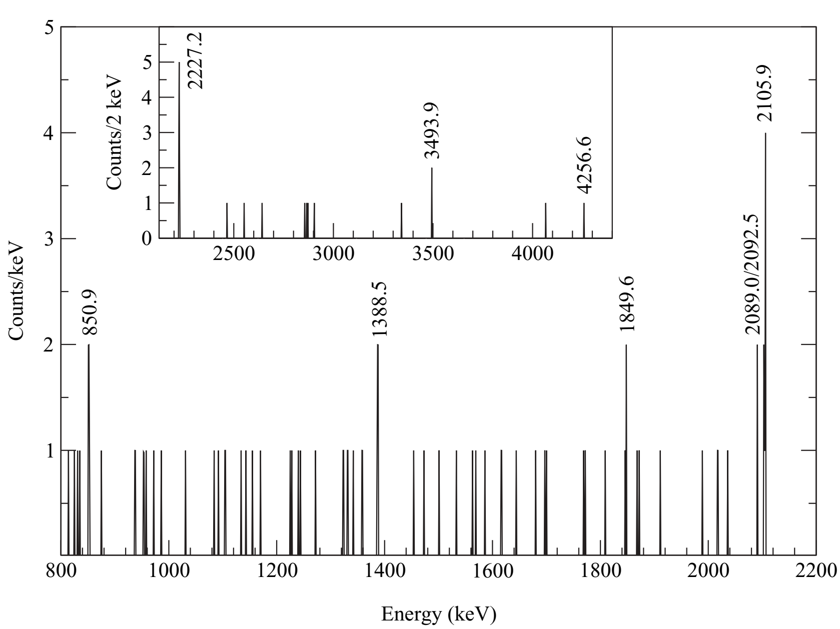

FIG. 6. Beam-on spectrum of γ rays in coincidence with the 953.9-keV γ ray.

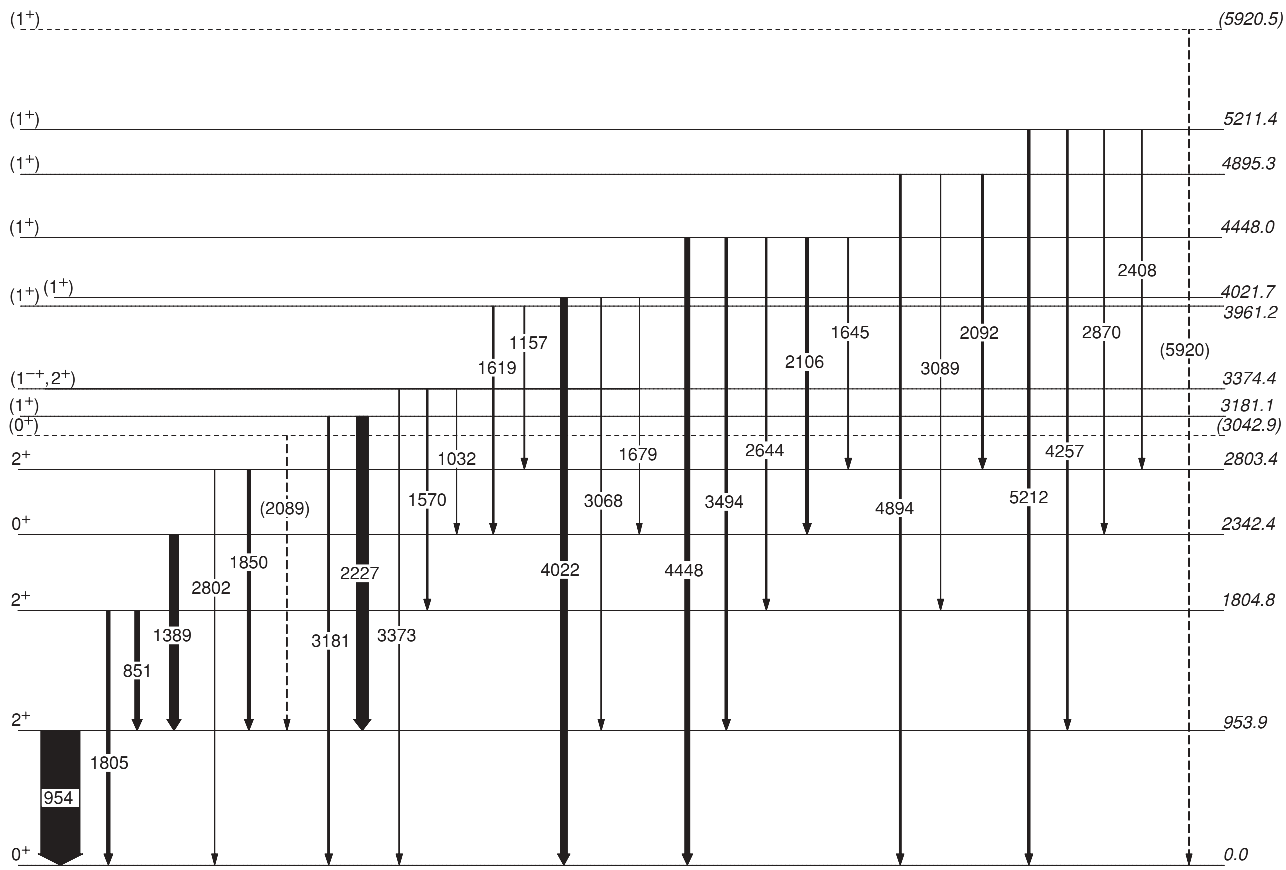

FIG. 7. ^{62}Zn decay scheme for levels populated in the β^+ decay of ^{62}Ga. The thickness of the arrows represents the relative intensities of the γ rays. Dashed lines represent tentatively assigned transitions and levels.

levels and their subsequent γ decay to the ground state may go undetected but could potentially sum to a non-negligible contribution. This is the "Pandemonium" problem articulated in Ref. [23] and further developed for the specific case of $A \geqslant 62$ superallowed decays in Ref. [22]. We have now developed techniques to overcome this challenge through a combination of detailed spectroscopy and the use of theory to calculate branching ratios averaged over many weakly populated states. The fifth column in Table I lists the difference of intensities of γ rays observed exiting from a state, $I_{\rm out}$, and the intensities of those γ rays observed feeding the state, $I_{\rm in}$. For 1^+ states, this difference is interpreted primarily as β feeding in Gamow-Teller transitions from ^{62}Ga, although unobserved γ feeding from above cannot be ruled out. For 0^+ states, this difference is a combination of β feeding in nonanalog Fermi transitions from ^{62}Ga and unobserved γ feeding from higher lying levels. For 2^+ states, this difference is entirely due to unobserved γ feeding from above, since the direct β decay to these levels is a second forbidden process and is expected to be negligible. For the three lowest 2^+ states identified in this work, we find the unobserved γ-ray feeding, I'_{2^+}, to be $122(27) + 105(12) - 21(12) = 205(29)$ ppm. We now introduce the ratio $\overline{B}_{\rm gs}$, defined by

$$\overline{B}_{\rm gs} = \frac{I'_{\rm gs}}{I'_{\rm gs} + I'_{2^+}}, \qquad (6)$$

where $I'_{\rm gs}$ is the unobserved γ-ray feeding to the ground state that we are seeking to quantify. Knowledge of $\overline{B}_{\rm gs}$ would allow the determination of $I'_{\rm gs}$ in terms of the experimentally determined quantity I'_{2^+}.

To estimate $\overline{B}_{\rm gs}$ we have performed a shell-model calculation for ^{62}Ga β decay to ^{62}Zn and its subsequent γ decay. A modified surface delta interaction (MSDI) of Koops and Glaudemans [24] was used, where the four parameters were fit to reproduce spectra for nickel and copper isotopes in the $58 \leqslant A \leqslant 60$ region. The model space consisted of three protons and three neutrons restricted to the $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ single-particle orbitals outside of a closed ^{56}Ni core and the effective Gamow-Teller strength was quenched to $g_{A_{\rm eff}} = 0.73$ to account for the truncation of the full fp shell. The theoretical decay pattern is shown in Fig. 8 and is seen to be in generally good agreement with experiment, as are the energy level spacings. The ratio $\overline{B}_{\rm gs}$ is approximated from the shell-model calculation by

$$\overline{B}_{\rm gs} = \frac{\sum_i f_i \times r_i}{\sum_i f_i}, \qquad (7)$$

where f_i is the feeding intensity of the ith 1^+ state in the Gamow-Teller decay of ^{62}Ga, and r_i is the branching ratio for the ith 1^+ state to γ decay to the ground state of ^{62}Zn. We have considered a number of possible starting points for the

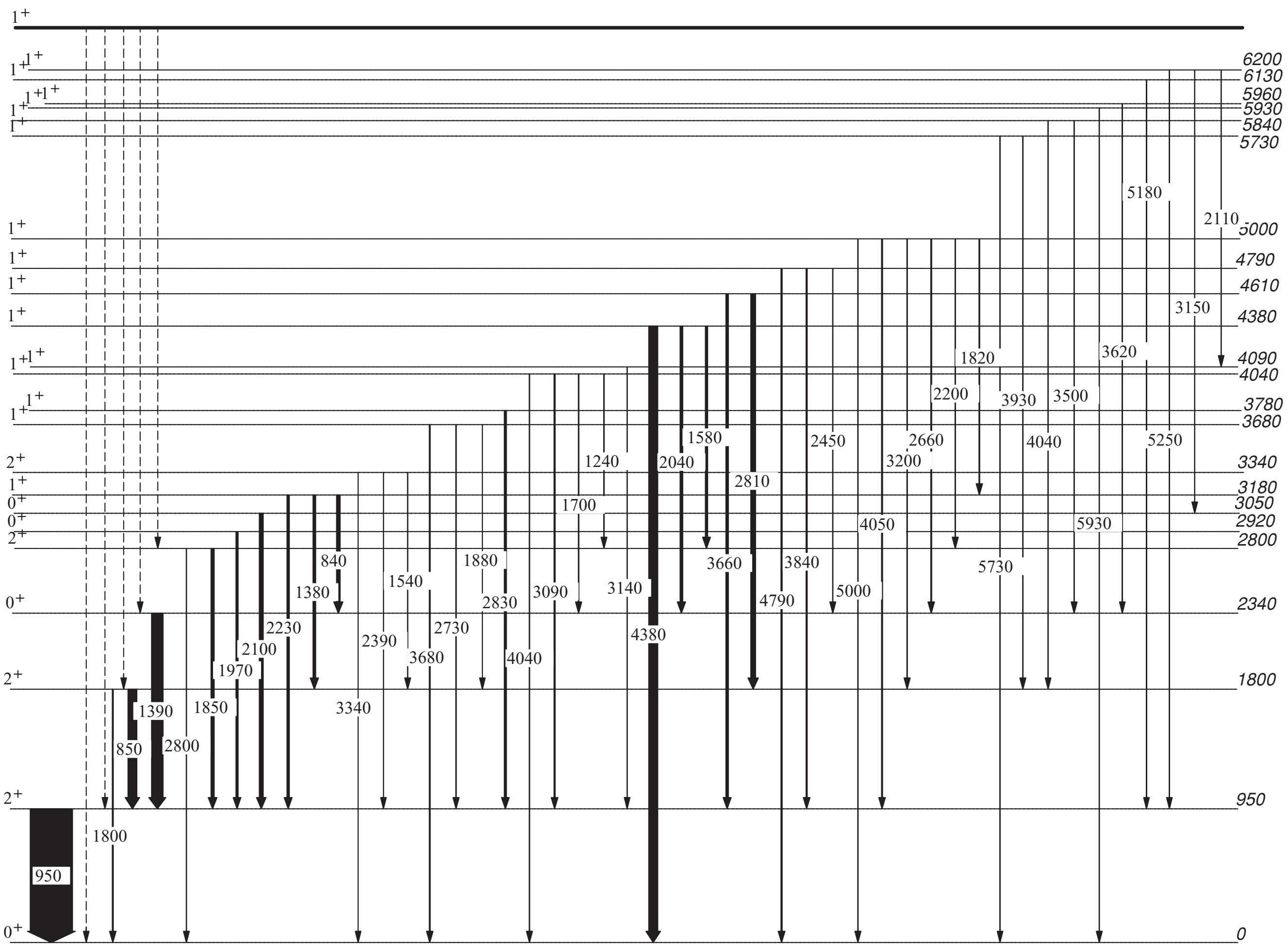

FIG. 8. Theoretical ^{62}Zn decay scheme for levels populated in the β^+ decay of ^{62}Ga, calculated by using the modified surface delta interaction of Koops and Glaudemans [24]. The thickness of the arrows represents the relative intensities of the γ rays. The thick level represents all higher lying 1^+ states, and the dashed lines represent the summed γ-ray intensities from all of these levels to the ground state and first four excited states.

summation index i. Simply summing over all 1^+ states in the shell-model calculation ($i = 1$) yields $\overline{B}_{\rm gs} = 0.195$. However, restricting the calculation of $\overline{B}_{\rm gs}$ to those high-lying 1^+ states likely to contribute to the *unobserved* γ-ray feeding yields $\overline{B}_{\rm gs} = 0.19$ starting at $i = 10$ ($E_{10} = 5730$ keV), $\overline{B}_{\rm gs} = 0.18$ starting at $i = 11$ ($E_{11} = 5840$ keV), and $\overline{B}_{\rm gs} = 0.21$ starting at $i = 12$ ($E_{12} = 5930$ keV). We thus adopt $\overline{B}_{\rm gs} = 0.20$ and assign what we consider to be a very conservative uncertainty of ± 0.20 to this theoretical value.

Referring to Eqs.(6) and(7), we see that the numerators in the two expressions for $\overline{B}_{\rm gs}$ are identical, whereas the denominators are only equal under the assumption that all of the intensity is collected in the ground state and first three excited 2^+ states. This assumption ignores the possible two-step decay of the 1^+ states to the ground state via intermediate 2^+_n states with $n > 3$, which can then decay directly to the ground state. In the shell-model calculation these decays represent less than 4% of the total unobserved intensity, a contribution that is rendered entirely negligible by our conservative $\pm 100\%$ uncertainty in adopting $\overline{B}_{\rm gs} = 0.20(20)$. While obviously including the lowest possible value of $\overline{B}_{\rm gs}$, we note that this range also encompasses the $\overline{B}_{\rm gs}$ value of 0.4 that is measured for the first six excited 1^+ states, which, statistically, are expected to have the largest values of $\overline{B}_{\rm gs}$. This range for $\overline{B}_{\rm gs}$ yields a range for the unobserved ground state γ intensity of

$$I'_{\rm gs} = \frac{I'_{2^+}\overline{B}_{\rm gs}}{1 - \overline{B}_{\rm gs}} = 0.000 - 0.0137(20)\%. \tag{8}$$

We thus adopt $I'_{\rm gs} = 0.008(8)\%$ to cover the entire plausible range for $\overline{B}_{\rm gs}$. Combining this with the observed ground-state intensity $I_{\rm gs} = 0.1338(26)\%$ gives a nonsuperallowed branching ratio of 0.142(8)% and a final superallowed β decay branching ratio for ^{62}Ga of 99.858(8)%.

We note that although the present experiment is statistically independent of our previous measurement of the ^{62}Ga branching ratio of 99.861(11)% reported in Ref. [7], these two experiments were conducted with the same apparatus and employed very similar analysis techniques. In particular, the systematic

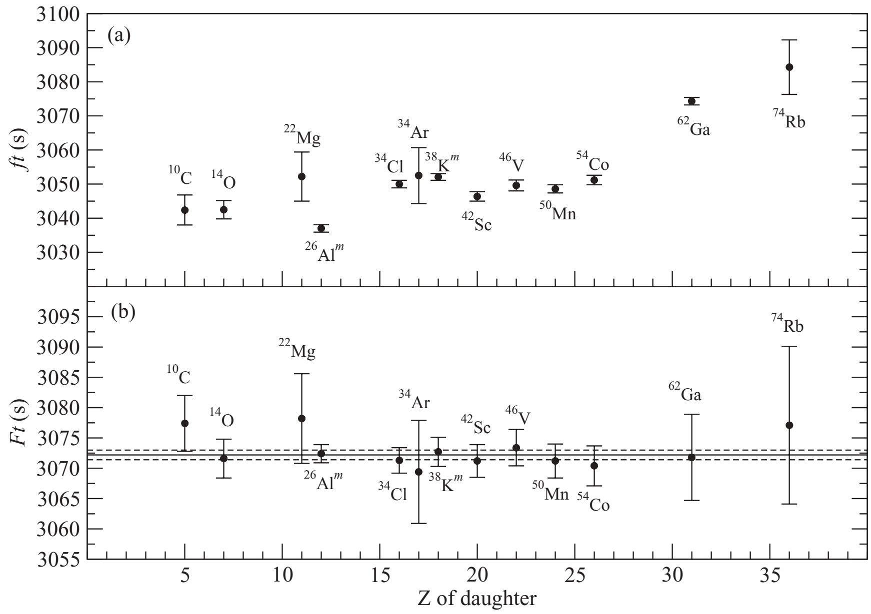

FIG. 9. Comparison of the superallowed ft and $\mathcal{F}t$ values for ^{62}Ga obtained in this work with the 12 other precision cases. The $\mathcal{F}t$ values were obtained with the δ_C corrections of Ref. [2] and, in addition to the data of Ref. [2], include the updated ^{62}Ga branching ratio reported here, the new world-average half-life of ^{62}Ga reported in Ref. [14], a new half-life measurement for ^{10}C in Ref. [25], the ^{38m}K branching ratio of Ref. [26], and the recent ^{50}Mn and ^{54}Co $Q_{\rm EC}$ value measurements of Ref. [27], leading to a world average $\overline{\mathcal{F}t} = 3072.2(8)$s with $\chi^2/\nu = 0.27$.

uncertainty associated with the theoretical $\overline{B}_{\rm gs} = 0.20(20)$ is common to both results and now completely dominates the uncertainty in the extracted superallowed branching ratio for ^{62}Ga. We therefore do not average our current result with our prior work, but we simply supersede the previous experiment with the more precise result 99.858(8)% obtained in the higher statistics experiment reported here.

IV. DISCUSSION

A. Isospin-symmetry breaking and the ^{62}Ga ft and $\mathcal{F}t$ values

The world average for the ^{62}Ga half-life has recently undergone a significant decrease owing to the addition of a new high-precision measurement [14] that, when combined with the seven previous results, yields $T_{1/2} = 116.121(21)$ ms. Combined with the superallowed branching ratio 99.858(8)% from this work, the calculated electron capture fraction $P_{\rm EC} = 0.137\%$ [1], and the phase-space integral $f = 26401.6(83)$ [16], the ^{62}Ga superallowed ft value is determined to be $ft = 3074.33(25)_{\rm BR}(56)_{T_{1/2}}(97)_f$ s $= 3074.3(11)$ s. With a precision of ± 1.1s, the current measurement for ^{62}Ga is among the most precisely determined superallowed ft values, as shown in Fig. 9(a). Its precision is now limited by the single high-precision $Q_{\rm EC}$ measurement of Ref. [16], for which an additional high-precision measurement would clearly be of value.

By using the nucleus-dependent corrections $\delta'_R = 1.459(87)\%$, $\delta_{\rm NS} = -0.045(20)\%$, and $\delta_C = 1.48(21)\%$ of Ref. [2], the corrected $\mathcal{F}t$ value for ^{62}Ga becomes $\mathcal{F}t = 3071.8(11)_{\rm exp}(26)_{\delta'_R}(6)_{\delta_{\rm NS}}(65)_{\delta_C}$ s $= 3071.8(71)$ s. This result is in excellent agreement with the world-average $\overline{\mathcal{F}t} = 3072.2(8)$ s [Fig. 9(b)] obtained with the δ'_R, $\delta_{\rm NS}$, and δ_C corrections for the 13 precision cases from Ref [2], updated with the latest ^{62}Ga half-life, ^{10}C half-life, $^{38}K^m$ branching ratio, and ^{50}Mn and ^{54}Co $Q_{\rm EC}$ value measurements of Refs. [14], and [25–27], respectively. We note, however, that for ^{62}Ga the uncertainty in the corrected $\mathcal{F}t$ value is now completely dominated by theory, and the isospin-symmetry-breaking correction δ_C in particular. With the CVC hypothesis validated as shown in Fig. 9(b), we can thus take the world-average $\overline{\mathcal{F}t}$ for the other 12 precision superallowed cases [which is also 3072.2(8)s] and, using our experimentally determined ft value for ^{62}Ga in conjunction with Eq. (1), extract an "experimental" δ_C by enforcing CVC.

The values $\delta'_R = 1.459(87)\%$ and $\delta_{\rm NS} = -0.045(20)\%$ of Ref. [2], combined with $ft = 3074.3(11)$ s from the present work, gives a δ_C value for ^{62}Ga of

$$\begin{aligned}\delta_C &= 1 - \frac{\overline{\mathcal{F}t}}{ft(1+\delta'_R)} + \delta_{\rm NS}\\ &= 1.462(37)_{ft}(26)_{\overline{\mathcal{F}t}}(84)_{\delta_{R'}}(20)_{\delta_{\rm NS}}\%\\ &= 1.46(10)\%. \end{aligned} \tag{9}$$

This result is in excellent agreement with the value of $\delta_C = 1.48(21)\%$ calculated in Ref. [2], confirming the internal consistency of these δ_C calculations, even for the case of the comparatively large δ_C in ^{62}Ga. Similar results for the 12 other precisely measured superallowed cases are shown in Fig. 10(a) and compared with the new δ_C evaluations of Ref. [2]. Although the overall average agreement is enforced by the use of $\overline{\mathcal{F}t}$ in Eq.(9), we note that the case-by-case variations (i.e. differences) in δ_C represent a real test of the theoretical model. The excellent agreement between theory and experiment is thus a strong confirmation of the isospin-symmetry-breaking calculations of Ref. [2].

The same analysis can be performed by using the $\overline{\mathcal{F}t}$ value 3076.2 ± 0.8 s with $\chi^2/\nu = 1.68$ determined with the δ_C correction terms of Ref. [6]. In this case the extracted δ_C for ^{62}Ga becomes 1.33(10)%. This is consistent with the range $\delta_C = 1.26\%$–1.32% calculated with Hartree-Fock wave functions in Ref. [6] but not with the range $\delta_C = 1.60\%$–1.70% calculated with Woods-Saxon wave functions [6]. Results for the 12 other precision cases are shown in Fig. 10(b) and compared with the calculations of Ref. [6], with the overall

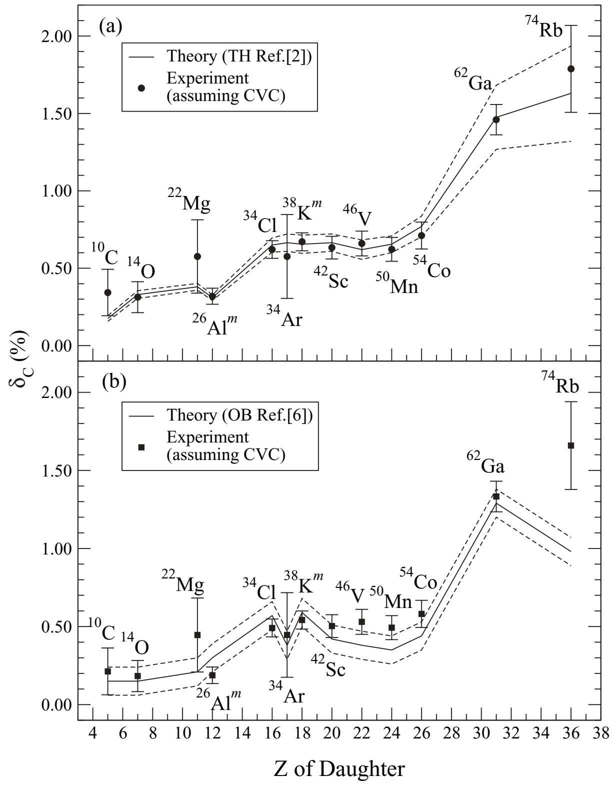

FIG. 10. Comparison between "experimental" δ_C correction terms deduced via Eq. (9) for the 13 precision cases with those calculated in (a) Ref. [2] and (b) Ref. [6]. The dashed lines in (a) and (b) show the uncertainty ranges adopted in Refs. [2] and [6], respectively.

$\pm 0.09\%$ theoretical uncertainty in δ_C adopted in Ref. [6] shown by the dashed lines. The agreement between theory and experiment for the case-by-case δ_C variations is not as impressive as in Fig. 10(a). We note, however, that the Hartree-Fock calculations of Ref. [6] do not yet include the important core orbital contributions discussed in Ref. [2].

We further note that $\delta_C = 1.46(10)\%$, extracted for ^{62}Ga with the corrections of Ref. [2], is determined with a relative precision better than 7% of its own value, more than twice the precision of the 14% relative uncertainty adopted in the theoretical value of Ref. [2] and, fractionally, the most precise δ_C value determined for any of the superallowed emitters. This large and precisely measured isospin-symmetry breaking in ^{62}Ga superallowed decay thus provides a benchmark for the refinement of isospin-symmetry-breaking calculations in $A \geqslant 62$ nuclei.

It should also be noted that while the δ_C for ^{62}Ga reported here has the highest relative precision for any superallowed emitter, to take full advantage of the very high precision experimental ft value for ^{62}Ga to test isospin-symmetry-breaking calculations it will also be necessary to consider higher order QED radiative corrections for the high-Z superallowed emitters. As can be seen in Eq.(9), the uncertainty in the "experimentally" determined δ_C value for ^{62}Ga is actually dominated entirely by the uncertainty in the radiative correction term δ'_R, which results from the truncation of this radiative correction at order $Z^2\alpha^3$ [28], a non-negligible order for the high-Z emitters such as ^{62}Ga. Some steps have been taken in the direction of extending superallowed radiative corrections to higher order [29], but there is now even stronger motivation to reduce the theoretical uncertainty in the δ'_R corrections for the high-Z nuclei to provide even more stringent tests of the isospin-symmetry-breaking calculations.

B. The isospin-mixing components $\delta^1_{C_1}$ and $\delta^{2-3}_{C_1}$

The reproduction of the case-by-case variations of δ_C in Fig. 10 indicates an overall impressive agreement between experiment and theory, but even more detailed tests of the calculations are obtained from the state-by-state isospin-mixing components $\delta^i_{C_1}$.

The first term $\delta^1_{C_1}$ is determined by the β branching ratio to the first-excited nonanalog 0^+ state in the decay of ^{62}Ga multiplied by the ratio of the phase-space integrals f for the ground state and first excited 0^+ state [Eq.(5)]. The difference in total intensity of the γ decay to γ feeding of 0^+_1 identified in this work is $I_{\rm out} - I_{\rm in} = 64(14)$ ppm. To extract the nonanalog β decay branch to this state, however, one must consider contributions from unobserved γ-ray feeding from higher lying levels, as well as unobserved γ decay of this level. To quantify these contributions peaks were fit at the locations of the unobserved transitions to the 0^+_1 level from the higher lying 1^+ and 2^+ states identified in this work as well as the unobserved γ decay from the 0^+_1 level to the 2^+_2 level at excitation energy 1804.88(20) keV. The difference of the total unobserved γ feeding and decay of 0^+_1 involving all other observed levels in Fig. 7 resulted in a contribution to the population of the 0^+_1 state of 0(19) ppm, where the uncertainty arises from adding the uncertainties associated with the fits to the peak areas of all the unobserved transitions in quadrature.

Finally, we must also estimate the possible unobserved γ-ray feeding of 0^+_1 from unobserved 1^+ levels above the gap in the level scheme that appears at $\sim$5.2 MeV in experiment and 5.0 MeV in the shell-model calculation. We turn again to theory. In the MSDI calculation the feeding of the 0^+_1 level from these 1^+ states represents 7.8% of the total γ feeding, or $0.078/(1-0.078) = 8.5\%$ of the feeding from below $\sim$5 MeV. The total γ feeding observed from below 5.2 MeV was 127 ppm, yielding an estimate for the unobserved feeding from weakly populated 1^+ states of $127 \times 0.085 = 11(11)$ ppm, where we have again adopted a conservative 100% relative uncertainty in the theoretical estimate. We thereby determine the nonanalog β decay branch to the 0^+_1 state to be $64(14) - 0(19) - 11(11)$ ppm $= 53(25)$ ppm. With the ratio $(f_0/f_1) = 4.91$, the isospin-mixing component $\delta^1_{C_1}$ is determined to be $\delta^1_{C_1} = 0.026(12)\%$.

This value is lower, by a factor of 3, than the value $\delta^1_{C_1} = 0.083(20)\%$ obtained in the MSDI calculation by scaling the theoretical $\delta^1_{C_1} = 0.089\%$ by the square of the ratio of the theoretical and experimental energies for this 0^+ state, $(2.26/2.342)^2$, as discussed in Ref. [5]. The experimental limit is also lower by a factor of approximately 3 than $\delta^1_{C_1} = 0.079\%$ calculated with the FPVH shell-model interaction in Ref. [6] and completely rules out $\delta^1_{C_1} = 0.169\%$ obtained with the FPD6$*$ interaction [6]. All of the currently available calculations are thus significantly overestimating the isospin-mixing component to the first excited 0^+ state of ^{62}Zn.

If the 2089.0-keV γ ray described in Sec. III does in fact represent a transition between an excited 0^+ state at 3042.9 keV and the first excited 2^+ state at 953.9 keV, its intensity sets an upper limit on the direct β feeding of this nonanalog 0^+ state. Assuming that this is the third excited 0^+ state (predicted to be strongly populated in the MSDI calculation), the 2089.0-keV γ-ray branching ratio of 12(5) ppm from Table I combined with the ratio of the phase-space integrals $(f_0/f_3) = 8.92$ yields $\delta^3_{C_1} \leqslant 0.011(4)\%$. The MSDI calculation, however, predicts a scaled $\delta^3_{C_1} = 0.203\%$, which would give a direct β branch of 227 ppm to the third excited 0^+ state. This state is predicted to decay by a 99.6% γ branch to the first excited 2^+ state, giving a γ-ray intensity of 226 ppm. The experimental upper limit is nearly a factor of 19 lower than the theoretical prediction, both in terms of the observed γ-ray intensity and the isospin-mixing component $\delta^3_{C_1}$. If the 2089.0-keV γ ray does not originate from the decay of the third excited 0^+ state, there is no evidence for *any* γ decay from this energy region with an intensity of even 10 ppm, which would impose an even lower limit on both the nonanalog branching ratio and $\delta^3_{C_1}$ and lead to an even larger discrepancy between experiment and theory.

Although such state-by-state comparisons represent a particularly severe test of theory, we note that in the MSDI calculation mixing to the first three excited 0^+ states, $\delta^1_{C1} + \delta^2_{C1} + \delta^3_{C1} = 0.292\%$, represents more than 80% of the total isospin mixing $\delta_{C1} = 0.347\%$ out of the ground state. The experimental limits presented here, however, provide no evidence for isospin mixing to low-lying 0^+ states exceeding, in total, 0.037(13)%. Either the theory must therefore be grossly overpredicting the total isospin-mixing correction δ_{C1} or the mixing must be occurring predominantly with more highly excited 0^+ states, a scenario that is also in contradiction with theory.

To explore sensitivity to the shell-model interactions, a calculation for ^{62}Ga was also performed [2] with the GXPF1 interaction [30,31], albeit truncated to the assumption of a closed ^{56}Ni core for which it was not designed. Not surprisingly, the reproduction of the ^{62}Zn spectrum is not as good with the truncated GXPF1 interaction as with the MSDI interaction designed for this model space. The GXPF1 calculation does remove the "problem" of the large predicted $\delta^3_{C_1}$ in the MSDI calculation, with no large mixing with any nonanalog 0^+ state above the first excited one appearing in the GXPF1 calculation. The consequence, however, is a much larger predicted $\delta^1_{C_1} = 0.158\%$ in the GXPF1 calculation, some six times the value of $\delta^1_{C_1} = 0.026(12)\%$ determined in this work.

Thus, although the overall δ_C calculations are in good agreement with experiment, the isospin-mixing components $\delta^i_{C_1}$ with the low-lying excited 0^+ states appear to be significantly overestimated in all shell-model calculations for ^{62}Zn to date. These calculations share the common assumption of a closed ^{56}Ni core, an assumption known to be rather strongly broken in this mass region [31], and it would appear that the improved calculation of isospin-symmetry breaking in the $A \geqslant 62$ superallowed decays will require the challenging, but necessary, lifting of this model-space truncation.

V. CONCLUSION

A high-precision superallowed branching ratio measurement for the nucleus ^{62}Ga was performed at the TRIUMF-ISAC facility in Vancouver, Canada. A total of 30 γ rays were identified following $6.3355(6) \times 10^8$ observed β^+ decays of ^{62}Ga, establishing the superallowed branching ratio to be 99.858(8)%, the highest precision superallowed branching ratio in the $A \geqslant 62$ mass region to date. Combined with the most recent half-life and Q-value measurements, this branching ratio yields an ft value of 3074.3(11) s that rivals the precision of the best measured superallowed decays. By comparing the superallowed ft value determined in this work with the world-average $\overline{\mathcal{F}t}$, stringent tests were made of the isospin-symmetry-breaking correction terms δ_C, $\delta^1_{C_1}$, and $\delta^{2-3}_{C_1}$. Although the overall δ_C correction appears to be in good agreement with experiment, the isospin-mixing contributions $\delta^i_{C_1}$ of the low-lying excited nonanalog 0^+ states are significantly overestimated in the shell-model calculations. These calculations share a common assumption of a closed ^{56}Ni core, a truncation that will have to be overcome to improve the calculations of isospin-symmetry-breaking corrections in the $A \geqslant 62$ superallowed β decays. The experimental value of $\delta_C = 1.46(10)\%$ for ^{62}Ga decay deduced here by assuming the validity of the CVC hypothesis is precise to better than 7% of its own value, the most precise fractional determination for any superallowed decay, and establishes a benchmark to further refine theoretical developments in this region.

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