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Precision Measurement of the $^6$He Half-Life and the Weak Axial Current in Nuclei

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H.E. Swanson, I.S. Towner, S. Utsumo, W. Williams, and C. Wrede

1 Department of Physics and Center for Experimental Nuclear Physics and Astrophysics, University of Washington, Seattle, Washington 98195, USA
2 Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA
3 Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA

Background: The beta decays of $^3$H and $^6$He can play an important role in testing nuclear wave-function calculations and fixing low-energy constants in effective-field theory approaches. However, there exists a large discrepancy between previous measurements of the $^6$He half-life.

Purpose: Our measurement aims at resolving this long-standing discrepancy in the $^6$He half-life and providing a reliable $ft$-value and Gamow-Teller matrix element for comparison with theoretical ab-initio calculations.

Method: We measured the $^6$He half-life by counting the beta-decay electrons with two scintillator detectors operating in coincidence.

Results: The measured $^6$He half-life is $806.89 \pm 0.11_{\text{stat}}^{+0.23}_{-0.19_{\text{sys}}} \text{ ms}$ corresponding to a relative precision of $3 \times 10^{-4}$. Calculating the statistical rate function we determined the $ft$-value to be $803.04^{+0.26}_{-0.23}$ s.

Conclusions: Our result resolves the previous discrepancy by providing a higher-precision result with careful analysis of potential systematic uncertainties. The result provides a reliable basis for future precision comparisons with ab-initio calculations.

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I. INTRODUCTION

Precision measurements of electroweak processes in light nuclei can provide important tests of our understanding of electroweak interactions in the nuclear medium. Many interesting problems – ranging from solar fusion to neutrino interactions and muon and pion capture processes – depend on their correct modeling and calculation [1]. Recent progress in numerical techniques enables precise, ab-initio calculations of wave functions for light nuclei starting with the nucleon-nucleon interaction and without assuming a frozen core of inactive particles [2–4].

The allowed weak nuclear decays driven by the axial current – called Gamow-Teller decays – have historically played an important role in testing wave functions because the main operator has a simple spin and isospin structure and does not possess any radial component. Systematic comparisons using shell-model wave functions showed that in order to reproduce observations the value for the weak axial coupling constant, $g_A$, had to be “quenched”. For the sd-shell nuclei this difference amounted to about 30% with respect to that measured in free neutron decay [5, 6]. In addition, when charge-exchange reactions were used to explore a large fraction of the Gamow-Teller strength sum rule, evidence also pointed to “quenching of the Gamow-Teller strength” [7, 8]. However, the origin of the quenching is not completely clear. References [7, 9, 10] have shown that, as shell-model calculations are allowed to introduce higher and higher excitations, the need to renormalize operators disappears. But it has also been pointed out that meson-exchange currents (mediating, for example, nucleon-delta excitations) could be responsible for at least some of the apparent quenching of strength [11, 12].

The decays of $^3$H and of $^6$He are special because these systems are light enough that the corresponding ab-initio calculations can be performed with precision. In particular, Refs. [4, 13] and later [14, 15] have shown that, using the case of $^3$H to fix nucleon-delta excitations, the $ft$-value for $^6$He can be calculated to within a few percent. These two decays, then, can play an important role in testing the accuracy of nuclear wave-function calculations [4, 13, 14], or as suggested in Ref. [15], in fixing low-energy constants in effective-field theory calculations [1].

In this paper we present a more detailed description of the high-precision experimental determination of the half-life and $ft$-value for $^6$He published in [16]. Except for a small branch of $\sim 10^{-6}$ [17] the beta decay of $^9$He proceeds 100% to the ground state of $^9$Li with an endpoint of 3.5 MeV. The $^6$He half-life has been previously determined by several works compiled in Table I and shown in Fig. 1. As can be seen, the values spread over a range much wider than expected from the claimed uncertainties which makes the currently reported average and precision of $806.7 \pm 1.5$ ms [36] unreliable. Averaging the five values shown in the insert in Fig. 1 with uncertainties below 1% and scaling the uncertainty by the square root of the $\chi^2$/dof – as advised by the Particle Data Group in such
TABLE I. Compilation of all previously obtained $^6$He half-life values.

<table>
<thead>
<tr>
<th>Year</th>
<th>Half-life [ms]</th>
<th>Reference</th>
<th>Year</th>
<th>Half-life [ms]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1948</td>
<td>820 ± 60</td>
<td>[22]</td>
<td>1962</td>
<td>797 ± 3</td>
<td>[23]</td>
</tr>
<tr>
<td>1952</td>
<td>860 ± 30</td>
<td>[26]</td>
<td>1974</td>
<td>808.1 ± 2.0</td>
<td>[29]</td>
</tr>
<tr>
<td>1952</td>
<td>840 ± 30</td>
<td>[28]</td>
<td>1981</td>
<td>798.1 ± 1.0</td>
<td>[31]</td>
</tr>
<tr>
<td>1953</td>
<td>830 ± 30</td>
<td>[30]</td>
<td>1982</td>
<td>805.4 ± 2.0</td>
<td>[33]</td>
</tr>
<tr>
<td>1954</td>
<td>799 ± 3</td>
<td>[32]</td>
<td>1983</td>
<td>808.5 ± 2.0</td>
<td>[34]</td>
</tr>
<tr>
<td>1955</td>
<td>850 ± 30</td>
<td>[34]</td>
<td>2002</td>
<td>810 ± 8</td>
<td>[35]</td>
</tr>
</tbody>
</table>

FIG. 1. (Color online) Compilation of the measured $^6$He half-lives given in Table I. The dashed blue band shows the half-life adopted in Ref. [36] from the average of the two values found in Ref. [29, 33] and used in compilations ever since. The inset shows the five values with uncertainties below 1% [23, 29, 31–33] with the dashed red band depicting the value for the $^6$He half-life obtained in this paper.

II. EXPERIMENTAL SETUP

We produced $^6$He using the tandem Van de Graaff accelerator available at the Center for Experimental Nuclear Physics and Astrophysics of the University of Washington. A deuterium beam impinging on molten lithium held in a stainless steel cup produced $^6$He via the reaction $^7$Li($^2$H,$^3$He)$^6$He. The $^6$He atoms subsequently diffused out into vacuum. A detailed description of the $^6$He source, which can deliver more than $10^9$ atoms/s to experiments, can be found in Ref. [38]. The $^6$He atoms were transferred from the source through a turbo-molecular pump to a low-background experimental area. The measuring volume consisted of a 35 mm diameter, 381 mm long tube made of stainless steel sealed on one side by a 254 $\mu$m thin copper foil and on the other by a spring loaded, viton O-ring sealed valve. Randomly distributed over our measurement period of five days we inserted a 19 mm diameter, 283 mm long stainless steel cylinder suspended in the center of the tube by four screws. With the stainless steel insert we increased the wall collision frequency of $^6$He atoms by about 80% and used that data to check for possible diffusion of the $^6$He atoms into the stainless steel surfaces. We took comparable amounts of data with and without this insert. Figure 2 shows a schematic drawing of the setup.

Directly in front of the measuring volume we placed two identical, 2.5 mm thick plastic scintillators separated by 3.2 cm registering the betas from the decay of $^6$He penetrating through the copper foil. The plastic scintillators were coupled via lightguides to Hamamatsu photomultiplier tubes model R1450. Their output signals passed through timing filter amplifiers (Ortec model 474) providing $\sim 100$ ns long pulses with a $\sim 30$ ns rise time. Two discriminators (LeCroy model 821) with thresholds right above the electronic noise provided the logic trigger signals. We formed the coincidence of those two signals resulting in a single 25 ns long logic pulse. We passed this
pulse through four gate generators (LeCroy model 222) providing signals of fixed, nonextendable dead times of lengths 1.9819(81) µs, 3.9990(81) µs, 6.0026(83) µs, and 7.9758(83) µs. The details of the dead time determination are given in Section IV. Subsequently, the four signals were fed into a CAMAC based scaler (LeCroy model 2551) together with the original coincidence signal and the signals from a 1 and 100 kHz clock. The signal from the 1 kHz clock also triggered the readout of the scaler module via the software package JAM [39] thereby providing 1 ms time stamps to our data stream. The 100 kHz clock was used to detect potential scaler reading problems. These data were written to event files for off-line analysis. A schematic of the whole electronics chain is shown in Fig. 3.

The timing sequence of the measurement was as follows: The data was acquired in 24 s long measurement cycles. During a period of 8 s we directed the deuteron beam onto the lithium target and the outlet of the turbo-molecular pump was connected to our measuring volume while the valve to the roughing pump was closed. For the following 16 s, thereby completing one cycle, we deflected the deuteron beam at the low-energy end of the accelerator, closed the spring loaded valve at the back of the measuring volume and measured the $^6$He half-life directly by observing the decay curve. At the same time the valve to the roughing pump opened and the $^6$He exhaust was pumped away. During the last 100 ms of the 16 s decay time both valves were open in order to provide some pumping to the measuring volume.

With separate electronics, we performed pulse height measurements at the beginning of the measurements to determine our thresholds. We triggered the ADC on the coincidence signal and took the pulse height spectra for both scintillators. Fitting the peak for the minimum ionizing particles we determined that $\sim 99\%$ of the pulses (in each of the detectors separately) are above our threshold. The thresholds were estimated to be $\sim 30$ keV based on the average energy deposition in the detector of $\sim 300$ keV for a minimum ionizing particle.

III. DATA PROCESSING

We read the binary JAM-files into ROOT [40] and created “raw histograms” with 1 ms bin size for each channel. At this stage, two main data defects could be detected: Missed readings due to the DAQ computer not reading out the scaler values and incorrect readings due to the scaler values updating while being read. Both of the defects were readily identified in the data stream. As the scaler retained the actual data unaffected by the missed and incorrect readings we were able to correct for them by distributing the counts of the next correct reading across the affected readings. From the raw histograms we created “differential histograms” for the different channels by calculating the differences between subsequent readings. The systematic uncertainties associated with this data correction are discussed in Section V.

In order to further reduce remaining data defects and improve the performance of the fitting at low statistics, we increased the bin size in the differential histograms to 10 ms. At the end we corrected for the dead time losses on a cycle-by-cycle basis by calculating the true rate $R_0$ in each time bin from the measured rate $R$ using the measured dead times $\tau_d$: $R_0 = R/(1 - R\tau_d)$ [41]. Because we took data at different deuteron beam intensities to study decay rate dependent effects, the data are finally grouped into five different initial rate classes: $< 40$ kHz, 40 - 50 kHz, 50 - 60 kHz, 60 - 70 kHz, 70 - 80 kHz.

IV. DEAD TIME MEASUREMENT

The dead time of the different channels was determined using the source and pulser method [42]. We placed a $^{90}$Sr source in front of the two scintillators to act as the random source. The pulser was running at 10 kHz. The signals from the source and the pulser were merged at the stage of the long gate generator. In a first step, we measured the rate with the random source only. After 15 - 20 min data acquisition, we read the total counts in each channel through the scaler. The total acquisition time was determined by a 10 Hz clock. In the next step, we performed the same measurement with the pulser on and determined the dead time by calculating [42]

$$\tau_d = \frac{1}{R_r} \left(1 - \frac{R_r - R_p}{R_r R_p} \right) \quad (1)$$

where $R_r$ is the rate of random signal, $R_p$ is the rate of the pulser and $R_{pr}$ is the rate of the mixed signal.

The intrinsic dead time from the start of the detector pulses to the generation of the long gates was inspected with an oscilloscope. It amounted to $\sim 130$ ns. As our long gates generated by the four gate generators were much longer than any preceding gates and signals, only the length of those four gates which we measured using the source and pulser method was relevant for the dead time correction. Several dead time measurements were performed following the $^6$He decay data taking. The results of those runs were consistent with each other. We averaged the different runs resulting in the dead times $1.9819(81)$ µs, 3.9990(81) µs, 6.0026(83) µs, and 7.9758(83) µs.

V. DATA ANALYSIS

Figure 4 shows the histogram for the full counting cycle for the data with initial rates $< 40$ kHz, 2 µs dead time and the stainless steel insert out. The step and wiggle right after 7.9 s is due to valve movement, when the valve of the decay volume is closed and the valve to the roughing pump is opened (we started the timing
FIG. 4. Histogram for a full $^6$He counting cycle for the data with initial rates $< 40$ kHz and the stainless steel insert out. The insert zooms into the transition point from beam-on to beam-off at which the valve in front of the measuring volume closes and the valve to the roughing pump opens.

100 ms after the beam turned on). It takes $\sim 200$ ms for this effect to die out. In addition, as the systematic uncertainty due to the dead time correction grows rapidly with rate we delayed the starting point of our fit in each of the rate groups such that for the highest rate in that group the initial rate lies at 32 kHz. For the group with initial rates $< 40$ kHz, the starting point is at 8260 ms - beyond the first 200 ms affected by the valve motion. The end point of the fit lies at 23900 ms. The fit was performed using the modified $\chi^2$ method outlined in Ref. [43]. Figure 5 shows the decay curve for the same data as in Figure 4. Also shown is a fit to the function $f(t) = N [\exp (- (t - t_0)/\tau) + b]$, where the lifetime $\tau$ and the background $b$ are free parameters while $N$ is set by the normalization of the fitting function and the total counts of the histogram. The lower panel gives the corresponding residuals. We cross-checked our fit results performing both regular $\chi^2$ and maximum likelihood fits. In addition, we performed the fits on simulated data consisting of $\sim 10^8$ random events distributed with a half-life of 807 ms and our measured background. Dead time effects were applied to the time-ordered events and then corrected in the same manner as for our experimental data. The results of the different methods for both the experimental and simulated data are listed in Table II showing their consistency and no particular bias.

Figure 6 shows a compilation of all the half-life fit results for the different rate groups and stainless steel insert in and out. The four different dead time channels were combined performing a weighted average and keeping the smallest of the statistical uncertainties. Table III gives the final results from the averages of the different rate groups. The individual dead time channels were combined to yield the two average values for the two cases corresponding to the stainless steel insert in and out of the measuring volume. These two values are used below for an estimation of the potential diffusion of $^6$He atoms into the stainless steel surfaces.

<table>
<thead>
<tr>
<th>Method</th>
<th>Exp. Data [ms]</th>
<th>Sim. Data [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modified $\chi^2$</td>
<td>806.969 ± 0.114</td>
<td>807.019 ± 0.096</td>
</tr>
<tr>
<td>Regular $\chi^2$</td>
<td>806.970 ± 0.114</td>
<td>807.025 ± 0.096</td>
</tr>
<tr>
<td>Max. likelihood</td>
<td>806.974 ± 0.113</td>
<td>807.023 ± 0.095</td>
</tr>
</tbody>
</table>

FIG. 6. (Color online) $^6$He half-life fit results for the different rate groups with the initial rates restrained to 32 kHz. Only statistical errors are given. The squares (circles) correspond to the stainless steel insert in (out) data. The dashed (solid) line shows the constant fit to the insert in (out) data with $\chi^2$/dof of 1.6/4 (3.4/3). The results of the constant fits correspond to the averages given in Table III.
TABLE III. List of the different $^6$He half-lives obtained with various dead times and for the cases of the stainless steel insert in and out. The systematic shifts and uncertainties from Table IV are not included.

<table>
<thead>
<tr>
<th>Insert</th>
<th>$\tau_d$</th>
<th>Results [ms]</th>
<th>Average [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>out</td>
<td>$\sim$2 µs</td>
<td>807.01 ± 0.11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\sim$4 µs</td>
<td>807.03 ± 0.11</td>
<td>807.03 ± 0.11</td>
</tr>
<tr>
<td></td>
<td>$\sim$6 µs</td>
<td>807.08 ± 0.11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\sim$8 µs</td>
<td>807.02 ± 0.11</td>
<td></td>
</tr>
<tr>
<td>in</td>
<td>$\sim$2 µs</td>
<td>807.20 ± 0.12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\sim$4 µs</td>
<td>807.20 ± 0.12</td>
<td>807.21 ± 0.12</td>
</tr>
<tr>
<td></td>
<td>$\sim$6 µs</td>
<td>807.21 ± 0.12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\sim$8 µs</td>
<td>807.23 ± 0.12</td>
<td></td>
</tr>
</tbody>
</table>

TABLE IV. List of systematic shifts and uncertainties for our $^6$He half-life measurement. We added the errors in quadrature to obtain the total error. Where a second value is given it corresponds to the measurements with the stainless steel insert in.

<table>
<thead>
<tr>
<th>Source</th>
<th>Shift [ms]</th>
<th>Uncertainty [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead time correction</td>
<td>0</td>
<td>0.04</td>
</tr>
<tr>
<td>Dead time drift</td>
<td>0</td>
<td>0.009</td>
</tr>
<tr>
<td>$^6$He Diffusion</td>
<td>0</td>
<td>$^{+0.12/-0.22}$</td>
</tr>
<tr>
<td>Gain shift</td>
<td>-0.19</td>
<td>0.19</td>
</tr>
<tr>
<td>$^8$Li contamination</td>
<td>0</td>
<td>$^{+0.03/-0.007}$</td>
</tr>
<tr>
<td>Data correction</td>
<td>0</td>
<td>0.01</td>
</tr>
<tr>
<td>Afterpulsing</td>
<td>0</td>
<td>0.003</td>
</tr>
<tr>
<td>Clock accuracy</td>
<td>0.006</td>
<td>0.011</td>
</tr>
<tr>
<td>Background</td>
<td>0.046</td>
<td>0.004</td>
</tr>
<tr>
<td>Total</td>
<td>-0.14</td>
<td>$^{+0.25/-0.19}$</td>
</tr>
</tbody>
</table>

VI. SYSTEMATIC UNCERTAINTIES

In Table IV we give our estimates of systematic shifts and uncertainties that are described in detail in the following paragraphs. In several cases we used a simulation to determine the magnitude of the systematic uncertainty. The simulation consisted of generating $\sim 10^{10}$ random events distributed with a half-life of 807 ms and our measured background. We then applied to the time-ordered events the different systematic effects and fit the data to determine the deviation from the input half-life.

The effect of the dead time correction is large. The correction shifts the half-life values by $-9$ ms, $-18$ ms, $-27$ ms, and $-35$ ms for the four different dead time channels, respectively. However, the agreement between the four values after the dead time correction lends confidence to its validity. The results for the different dead time channels are highly correlated and their differences should only be influenced by the corresponding loss in statistics, the uncertainty of which is given by

$$\sigma_{corr} = \sqrt{\sigma_1^2 - \sigma_2^2}. $$

Since our data for different dead time channels are not completely correlated due to the data preselection, we modified the data preselection procedure to result in the exact same data set for all the dead time channels. The results for this particular dataset are shown in Table V, together with the differences between the 2 µs channel and the other channels and their corresponding error as calculated according to the description above. The differences are consistent with the loss of statistics in the different dead time channels.

The uncertainty on the measured dead times of $\sim 8$ ns translates directly into a systematic uncertainty on the half-life. Figure 7 shows the dependence of the fitted half-life values on changes in the dead time as determined from data. The linear slope of $-0.00485$ ms/µs results in a systematic uncertainty of 0.04 ms. While a small and constant spread in the fixed dead times does not introduce any systematic uncertainty, a drift in the dead times obviously does. We tracked the length of the 2 µs gate during seven days on a digital oscilloscope. While we observed variations of $\pm 2$ ns on a daily basis there was no long term drift detectable. We attribute a systematic uncertainty of 0.009 ms in the half-life to these observed drifts.

Using a helium leak detector we studied the diffusion of helium through the walls of the measuring volume and the viton O-ring of the valve at its end. While we did not
observe any diffusion through the walls, we did observe the diffusion of helium atoms through the valve O-ring. Figure 8 shows the resulting helium gas flow into the leak detector with one side of the closed valve connected to its inlet and the other side filled to 1 atmosphere of helium. In our analysis we follow References [44–46]. We found acceptable agreement between our data and the predicted gas flow $C(t)$ as given in Eq. (46) of Ref. [44]

$$C(t) = C_0 \left[ 1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp \left( -\left( n\pi \right)^2 \frac{D t}{d^2} \right) \right]$$

for a diffusivity $D = 10^{-5} \text{ cm}^2/\text{s}$ and a steady-state flow $C_0 = 5.7 \times 10^{-8} \text{ mbar}/\text{s}$. The thickness $d$ of the O-ring in the valve was measured to be 2.2 mm. There is an uncertainty of about a factor of 2 in the extracted diffusivity due to the thickness and about 20% on the steady-state flow due to the sensitivity of the leak detector. From these two measurements we extract a permeability $K = 10^{-10} \text{ cm}^3 \text{ STP} \text{ mm}/\text{s}/\text{mbar}/\text{cm}^2$ using an exposed area of $A = 1.2 \text{ cm}^2$ and a solid solubility $b = 10^{-9} \text{ cm}^3 \text{ STP}/\text{mbar}/\text{cm}^3$ for helium in the viton O-ring of our valve. Both of these values are in acceptable agreement with values found in the literature. We neglect any mass scaling of the measured flow by $\sqrt{m_{\text{He}}/m_{\text{He}}}$ and an exponentially decreased diffusivity due to the higher mass. During our cycle length of $T = 16 \text{ s}$ the $^6\text{He}$ atoms diffuse a distance $l \sim 2\sqrt{D T}$ into the O-ring resulting in an absorbed gas volume $V_{\text{gas}} = 2\sqrt{D T} A b p_{\text{He}}$ at the $^6\text{He}$ partial pressure $p_{\text{He}}$. The average loss rate over the full cycle thus amounts to

$$\frac{1}{T} \frac{N_{\text{loss}}}{N_0} = \frac{1}{T} p_0 b \frac{2\sqrt{D T} A}{V_0} = 5 \times 10^{-9} \text{ 1/s}$$

with $p_0 = 1000 \text{ mbar}$, the total number of $^6\text{He}$ atoms $N_0$ and the volume of our measuring volume $V_0 = 367 \text{ cm}^3$. This represents a negligible shift at our precision.

Although we were not able to observe any diffusion through the walls of the measuring volume, we assume that some diffusion does occur leading to an additional loss channel. The mean free path $\lambda = 4V/A$ inside our measuring volume $V$ and surface area $A$ leads to a wall collision frequency $f_c = v/\lambda$ given the velocity $v$ of the atoms. Any time constant $1/\tau_{\text{diff}}$ associated with this loss channel scales linearly with the wall collision frequency $f_c = v/\lambda$ and will lead to a measured lifetime $1/\tau = 1/\tau_{\text{in}} + 1/\tau_{\text{diff}}$. From the absence of any significant difference between the two results listed in Table III we conclude that $\tau_{\text{diff}} \gg \tau_{\text{He}}$ and the difference between the two results is $\Delta (1/\tau) = 1/\tau_{\text{in}} - 1/\tau_{\text{out}} = (-2.8 \pm 2.5) \times 10^{-7} \text{ ms}^{-1} = 0.8/\tau_{\text{diff}}$ where the factor 0.8 is due to the 80% increased wall collision frequency with the insert in place. We set the Gaussian probability density function to zero in the nonphysical region [37] and calculate an upper limit on $1/\tau_{\text{diff}}$ at 68% C.L. of $2 \times 10^{-7} \text{ 1/ms}$. This translates into a systematic uncertainty for the insert in and out data of $+0.22\%$ and $-0.12\%$, respectively.

Examining our highest rate data we have identified traces of a small, rate-dependent shift, which is not fully accounted for by our dead time correction. Though pile-up effects could potentially be the cause of such a shift, based on the arguments given below its effect is too small to contribute. Therefore, because the values are shifted towards higher half-life values, we attribute it to a negative decrease in gain with increased rate in the photomultiplier tubes. For a potential reduction in gain of $10\%$ a fraction of $10^{-3}$ of the counts fall below threshold as determined from the pulse-height measurements performed at the beginning of the data taking. This would lead to a systematic shift of the half-life of 0.16 ms as obtained from our simulations and gives the approximate order of magnitude of such potential gain shifts. In order to investigate the size of the rate-dependent shift from our data constrained to 32 kHz itself, we added a parameter $k$ to our fitting function to model the effect of a linear rate dependence by substituting in our fitting function $R(t) \rightarrow R(t) (1 - kR(t))$. The resulting shift in the half-life due to including the parameter $k$ amounts to $-0.19 \pm 0.19 \text{ ms}$ showing no significant rate-dependent effect after corrections. We did not observe any difference in this shift between the two data sets with the stainless steel insert in or out. As a consistency check, we also examined our data by plotting the fit results as a function of start time shown in Fig. 9. As the start time of the fit is different in each of the rate groups the values are given as a function of “delay-time” corresponding to the delay of the start time in each rate group. The two solid lines on that plot correspond to the $\pm 1\sigma$ contours given by the loss in statistics for this correlated data set. The data around the rather large drop at about 3 s was studied in more detail in search for a potential artifact.
but we concluded there is no anomaly.

A potential contaminant in our system – apart from tritium, which cannot influence our measurement – is the beta emitter \(^8\)Li (\(t_{1/2} = 838.40(36)\) ms, \(\beta^-\) decay with endpoint 16.0 MeV \([47, 48]\)) produced by the reaction \(^7\)Li(\(^2\)H, \(^3\)He)\(^8\)Li. The Li atoms are not expected to reach our counting station but rather get trapped in the Li target or in the walls during the many collisions (\(\sim 10^5\)) that occur before atoms can reach the detection area. Nevertheless, in separate measurements using both of our two thin scintillators used for the half-life measurements but also a thick scintillator to measure the full energy of the betas, we scanned the deuteron beam energy below the \(^7\)Li(\(^2\)H, \(^3\)He)\(^6\)He reaction threshold of 5.8 MeV, but above the one for \(^8\)Li of 0.25 MeV \([48]\). While we still observed a small production rate of a beta emitter both the energy spectrum with an endpoint of 3.5 MeV and the extracted half-life of \(810 \pm 5\) ms clearly identify it as \(^6\)He. The observed production agrees with a rough estimate of it being produced by the reaction \(^6\)Li(n, \(^1\)H)\(^6\)He where the neutrons are produced via \(^7\)Li(\(^2\)H,n). Integrating the background-subtracted beta energy spectrum above the \(^6\)He endpoint and operating at our nominal deuteron beam energy we set an upper limit of \(2 \times 10^{-4}\) at 68\% C.L. on the fraction of possible \(^8\)Li contamination translating in a systematic uncertainty of 0.007 ms.

Throughout the data taking we performed several background runs in which we kept the valve in front of the measuring volume closed but otherwise operated the experiment just like for the other runs. Our background runs are distributed across all of the lifetime data and largely average out thechanges in background levels or deuteron beam current. While we initially saw a significant contribution stemming from \(^6\)He betas penetrating through the thin-walled stainless steel bellows of our roughing pump, we were able to greatly reduce that background by shielding the bellows with lead. The data taken before this provision were not included in the analysis. The measured background rate in background runs and the fitted background rate in half-life data taking runs are shown in Figure 10. The average background rate of the data taking runs was 0.8\(\pm 0.1\) Hz, which is consistent with the average of the rates of the background runs. Combining all the background run data after shielding the bellows, we still observed a small decay structure with a half-life of 507(27) ms and an amplitude of 6.3(3) times the value of the constant background in the background runs. While this is most probably still coming from \(^6\)He that is being pumped away it could also be the result of some beam-related activation. Regardless of its origin, we studied this time-dependent background by including it in the fitting function: 

\[
R(t) = N \exp(-(t-t_0)/\tau) + b(1 + A \exp[-(t-t_0)/\tau_b]),
\]

where \(A\) is the ratio of the amplitude of the extra decay structure and the background and \(\tau_b\) is the lifetime of the extra decay structure. We assumed that \(A\) was the same in the half-life data taking runs as that in the background runs. By varying \(A\) and \(\tau_b\) in the range measured in the background runs, we concluded that the extra decay structure results in a systematic shift of 0.046 ms with an uncertainty of 0.004 ms.

We studied our data-correction procedure outlined in Section III in detail using the simulation with the occurrences of the different defects determined from the data. We did not observe any significant shift within the statistical uncertainty of the simulation. We also performed our fits on the data without any data corrections resulting in a consistent value. We thus attribute a systematic uncertainty of 0.01 ms (the statistical uncertainty of our simulation) to our data-correction procedure.

In a dedicated effort we measured the time distribution between two consecutive coincidence events using a time-to-amplitude converter in order to search for spurious afterpulses due to electronic or instrumental effects. We found an excess of events in the 4 \(\mu\)s full range setting leading to a 0.7 \(\mu\)s wide peak at 0.75 \(\mu\)s sitting on top of an otherwise perfectly exponential behavior \([41]\) shown in Figure 11. The probability of occurrence of those excess
events is $3 \times 10^{-4}$. While we are protected from those excess events by the dead times we performed a simulation with such an excess centered at 3.5 µs to study its potential influence. Table VI lists the results of that simulation with the differences and associated uncertainty calculated as in the discussion on dead time above. There is a small effect visible in the 2 µs channel. As a conservative estimate of the systematic uncertainty we use the statistical uncertainty of the simulation of 0.01 ms. The after-pulse height is about 4 times the noise amplitude in Figure 11, so the systematic uncertainty for a frequency after-pulse height is about 4 times the noise amplitude in the range 0 to 0.75 µs.

We measured the precision of our 1 kHz clock by comparing the summed number of ticks over 16 days with respect to the time provided by NIST at Ref. [49]. The accumulated difference amounts to $-11 \pm 1$ ms over a period of $1.37 \times 10^6$ s, which corresponds to a shift of $-8.03 \pm 0.73$ ppm. Due to potential changes in temperature, we assign an additional 13.35 ppm to the frequency uncertainty. Therefore, we estimated the systematic shift and uncertainty to be 0.006 ± 0.011 ms.

Pile-up effects do not play a significant role in our measurement due to our long dead times and low threshold. One way that pile-up would influence our result is that two coinciding pulses below threshold result in a pulse above threshold. As given in Section II, the threshold cuts away ~1% of the electron spectrum in each scintillator. The probability of two pulses of length $\tau_p \approx 100$ ns coinciding at a given rate $R$ is given by $R\tau_p$. The probability that those two pulses are below threshold is $P_{pile} = 10^{-4}$. The correction that would need to be applied to the data thus takes the form $R_0 = R(1 - P_{pile}R\tau_p)$ in order to obtain the true rate $R_0$ given the measured rate $R$. Combined with the dead time correction, the final correction (neglecting higher order infinitesimals) looks like $R_0 \approx R/\left[1 - R(\tau_d - P_{pile}\tau_p)\right]$. Therefore, this pile-up effect behaves like a ~0.01 ms correction to the dead time, which leads to a negligible shift in our half-live value of $5 \times 10^{-5}$ ms. Another effect of pile-up would stem from the coincidence of two pulses directly at the end of the long dead time gate, which would thus not free the trigger at the appropriate time and extend the dead time. However, this requires the coincidence of three pulses, the probability of which is given by $(R\tau_p)^2$ corresponding to $\sim 10^{-5}$ at our highest rates. At the highest rates this leads to an extension of the dead time by a negligible 0.001 ms. Due to both effects being negligible we do not list them in Table IV.

### VII. RESULTS

As the result of our measurements with the stainless steel insert is dominated by the systematic uncertainty due to a potential diffusion of the $^6$He atoms into the surface we do not average the two values given in Table III. We report the data from our measurements without the insert as our final result yielding a $^6$He half-life of

$$T_{1/2} = 806.89 \pm 0.11_{stat}^{+0.23}_{-0.19 \text{ syst \ ms}}$$

where the first error is statistical and the second systematic.

From this, we proceed to determine the $ft$-value for the beta decay of $^6$He and extract the corresponding Gamow-Teller matrix element. We calculated the $Q$-value of the decay to be 3.505208(53) MeV/c² using the recent $^4$He mass determination obtained in a Penning trap [50] and the value for $^4$Li [51]. This corresponds to a $4\sigma$ shift compared to previously reported values [52]. The relation between the $ft$-value and the Gamow-Teller matrix element $M_{GT}$ is

$$f^*t(1 + \delta^GT_R)(1 + \delta^NS - \delta_C) = \frac{K}{G^2_V(1 + \Delta^GT_V)|M_{GT}|^2}$$

following the definitions and notation of Ref. [53]. We set the parameters $\delta^NS$ and $\delta_C$ to zero – or equivalently absorb them into the definition of $M_{GT}$ – and calculated the radiative correction $\delta_R^GT$ to be 1.0365(13)%.

We adopted the value for the parameters $K/\left|G^2_V(1 + \Delta^GT_V)\right| = 6143.62 \pm 1.66$ s from the world average of superallowed $0^+ \rightarrow 0^+$ nuclear beta decays [53]. The statistical rate function is given by $f^* = \int f(Z,E)pE(E - E_0)^2f_1(E)dE = f(1 + \delta_v)$ where $f$ is the value of the integral in the absence of the shape-correction function.
TABLE VII. List of shifts in the determination of the experimental Gamow-Teller matrix element.

| Source                          | Shift in $f^*$ | Shift in $|M_{GT}|$ |
|---------------------------------|---------------|---------------------|
| Shift in Q-value$^a$            | -0.51(10)%    | 0.26(5)%            |
| Improved radiative correction   | -             | 0.0299(6)%          |
| Shape factor $\delta_s$         | 0.19(6)%      | -0.09(4)%           |

$^a$ Shift due to the recent mass measurement of $^6$He with $\Delta Q/Q = -0.0860$% [50].

\[ f_1(E) \text{ and } \delta_s \text{ the correction to it when including } f_1(E). \]

Here $F(Z, E)$ is the Fermi function, $p$ and $E$ the electron momentum and energy, and $E_0$ the end-point energy. We obtain $f = 995.224(68)$ yielding an $ft$-value of 803.04$^{+0.26}_{-0.23}$ s, where we added the statistical and systematic errors in quadrature. In order to take into account the shape correction we performed shell-model calculations using the Cohen-Kurath interaction [54] and with the Warburton-Brown interaction, denoted PWBT in [55], adjusted to either reproduce the experimental Gamow-Teller matrix element or the weak magnetism term, which in Holstein’s notation [56] is $b = 68.4(7)$, determined from the width of the 0$^+ \rightarrow 1^+$ transition in $^6$Li [57]. Both adjustments result in almost identical terms for the statistical rate function and we obtain $f^* = 997.12(58)$. From this we calculate the experimental value for the Gamow-Teller matrix element in $^6$He beta decay as $|M_{GT}| = 2.7491(10)/|g_A|^3$. Using $g_A = -1.2701(25)$ [37] determined from the decay of the free neutron, we get $|M_{GT}| = 2.1645(43)$.

VIII. COMPARISON WITH THEORY

Given the precision obtained in our measurement it is worthwhile to itemize the improvements (both experimental and theoretical) that affect the extraction of the Gamow-Teller matrix element, $M_{GT}$. Table VII lists the shifts that have occurred in $M_{GT}$ arising from (a) an improvement in the $Q$-value determination, (b) an improvement in the calculation of the nucleus-dependent radiative correction, and (c) the inclusion or not of the shape-correction function in the statistical rate function calculation. The benchmark experimental $ft$-value that has been used by theorists [4, 13–15] up until now dates back to Ref. [58] and a statistical rate function obtained from the tabulated values of Wilkinson and Macfield [59]. By happenstance our half-life measurement agrees with the value adopted in [36] so no shifts due to a revision in the half life are included in Table VII. First, the improvement in the $Q$-value measurement leads to a 0.26% shift in the value of the Gamow-Teller matrix element. Second, the tabulated values of the statistical rate function of Wilkinson and Macfield include the radiative correction calculated to order $\alpha$. Today, it is normal to extend these calculations to order $Z\alpha^2$ and $Z^2\alpha^3$, see for example Ref. [60]. These extensions give a small shift in $M_{GT}$ of 0.03%. Third, the inclusion of a shape-correction function induces a small $-0.09%$ shift. That this shift is so small in $^6$He $\beta$ decay is a reflection of the fact that this transition is very fast and the ‘allowed’ approximation of ignoring the spectrum shape works very well. In more retarded transitions this correction would become more significant. The sum of these three shifts is quite small producing an experimental $M_{GT}$ value that is in agreement, within errors, of the one used previously in comparisons with theory. However, the extraction of the experimental Gamow-Teller matrix element given here stands on a more solid footing.

To make comparisons on the possible quenching of $g_A$ we define an experimental axial coupling constant for $^6$He, $^{6}_{\text{He}}g_A^e$, as

\[ |g_A|^6_{\text{He}} = \frac{1}{M_{\text{GT}}^{\text{calc}}} \sqrt{G_T(1 + \Delta V_R) f^* t (1 + \delta_R^c)(1 + \delta_{\text{NS}} - \delta_C)} \]

\[ = \frac{|g_A|^6_{\text{He}} |M_{\text{GT}}|^{\text{calc}}}{M_{\text{GT}}^{\text{calc}}} \]

using the calculated matrix elements $M_{\text{GT}}^{\text{calc}}$. Table VIII shows the comparison for the matrix elements between our experimental result and the different calculations and the experimental axial coupling constant for $^6$He and the one obtained from the free neutron. The two most recent calculations are off by about 1.5% with older calculations showing a difference of ~5%. Clearly the need for a large quenching of $g_A$ as observed in shell-model calculations of sd-shell nuclei is not needed here. Only Ref. [4] gives the calculated width of the analogous M1 transition in excellent agreement to within the experimental uncertainty of 2%. Interesting measurements to complement our result would be improved determinations of the M1 width and of the muon capture rate on $^6$Li [61] to a precision of $\lesssim$1%. The latter would directly test a possible momentum-transfer dependence of the effective weak axial coupling in nuclei [12].

IX. CONCLUSIONS AND SUMMARY

We have performed the most precise measurement of the $^6$He half-life of 806.89 ± 0.11stat$^{+0.23}_{-0.19}$ syst ms thereby improving the precision over the currently reported value [36] by a factor of 6. Our result is in good agreement with two of the previous five values [29, 33] with precisions of less than 1% but deviates from the three others by up to 8.6$\sigma$ [23, 31, 32]. Because the possibility of diffusion out of the target was not directly addressed in these experiments we speculate that this may be the cause of the discrepancy. Calculating the statistical rate function we determined the $ft$-value to be 803.04$^{+0.26}_{-0.23}$ s. The extracted Gamow-Teller matrix element of $|M_{GT}| = 2.1645(43)$ agrees within a few percent with ab-initio calculations using the weak axial coupling constant $g_A$ measured in free neutron decay. Our precise
TABLE VIII. Comparison between the experimental Gamow-Teller matrix element obtained in this work and the various calculations. As our measurement determines the product $|g_A| |M_{GT}|$ we present the comparison with theory by calculating $|g_A| |M_{GT}|/|M_{GT}|_{calc}$ and comparing it to the value for the axial coupling constant obtained from free neutron decay $g_A = -1.2701(25)$ [37]. LO stands for “leading order” and MEC for “meson-exchange currents”. Where two values are given they represent the results of different calculations by changing, e.g., the wave functions ($\Psi_T$) or nuclear potentials (AV8', TM' (99)) used. For the exact details on those changes and the calculations we refer to the provided references.

| Reference | Matrix element $|M_{GT}|$ | $|g_A| M_{GT}$ | $|g_A| M_{GT}$ (incl. MEC) | $|g_A| |M_{GT}|/|g_A|$ |
|-----------|--------------------------|---------------|---------------------------|---------------------|
| [13]      | 2.254(5) ($\Psi_T$ I)    | 2.284(5) ($\Psi_T$ I) | 1.204                     | -5.2%               |
|           | 2.246(10) ($\Psi_T$ II)  | 2.278(10) ($\Psi_T$ II) | 1.207                     | -5.0%               |
| [4]       | 2.283 (AV8 + TM' (99))   | 1.204         | -5.2%                     |
|           | 2.305 (AV8')             | 1.193         | -6.1%                     |
| [14]      | 2.157(1) ($\Psi_T$ I GFMC)| 1.275         | 0.4%                      |
|           | 2.207(3) ($\Psi_T$ II GFMC)| 1.246       | -1.9%                     |
| [15]      | 2.225(2)                 | 2.198(7)      | 1.251                     | -1.5%               |

this work | $|g_A| M_{GT} = 2.7491(10)$

Determination allows for improved comparisons between theory and experiment and may allow using $^6$He in addition to $^3$H to fix low-energy constants in the effective-field theory description of the electroweak processes.

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