

High Precision Measurement of the Superaligned $0^+ \rightarrow 0^+ \beta$ Decay of ^{22}Mg

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The half-life, 3.8755(12) s, and superallowed branching ratio, 0.5315(12), for ^{22}Mg β decay have been measured with high precision. The latter depended on γ -ray intensities being measured with an HPGe detector calibrated for relative efficiencies to an unprecedented 0.15%. Previous precise measurements of $0^+ \rightarrow 0^+$ transitions have been restricted to the nine that populate stable daughter nuclei. No more such cases exist, and any improvement in a critical Cabibbo-Kobayashi-Maskawa unitarity test must depend on precise measurements of more exotic nuclei. With this branching-ratio measurement, we show those to be possible for $T_z = -1$ parents. We obtain a corrected $\mathcal{F}t$ value of 3071(9) s, in good agreement with expectations.

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Superaligned $0^+ \rightarrow 0^+$ nuclear β decay is a sensitive probe of the vector part of the weak interaction. Measurement of the ft value for such a transition yields a direct determination of the vector coupling constant, G_V , provided that small radiative corrections are properly accounted for. Until now, the ft values for nine $0^+ \rightarrow 0^+$ transitions—the decays of ^{10}C , ^{14}O , ^{26m}Al , ^{34}Cl , ^{38m}K , ^{42}Sc , ^{46}V , ^{50}Mn , and ^{54}Co —have been measured with $\sim 0.1\%$ precision or better, and these results yield fully consistent values for G_V . With G_V thus determined, it is possible to establish a very precise value for V_{ud} , the up-down element of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix. Not only is this the most precise determination of V_{ud} , it is the most precise result for any element in the CKM matrix. It also leads to the most demanding test available of CKM unitarity, a fundamental tenet of the minimal standard model. Strikingly, the test fails by more than 2 standard deviations [1,2]: viz. $V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9968 \pm 0.0014$. Since recent results suggest that the value of V_{us} may need to be revised [3], it is even more important that the value of V_{ud} be known as precisely as possible.

Since the uncertainty in V_{ud} is dominated by the uncertainty in the small ($\sim 1\%$) calculated correction terms that are applied to the data, any improvement in the statistical definition of the unitarity test must come from improvements in those terms, two of which depend on structure details for the nuclei involved. It has recently been argued [1] that the best way to validate the structure-dependent correction terms is to measure additional superallowed transitions specifically selected to cover a wider range of correction-term magnitudes, demonstrating whether these transitions also produce consistent G_V values. To this end, we focus on the even-even $T_z = -1$ nuclei with $18 \leq A \leq 42$, selected because their decays are between nuclei described by the same nuclear-model spaces as those used for some of the nine currently well-known cases. Since the calculated correction terms are obtained in a completely consistent way, the tests of

these terms will have a direct impact on current results for V_{ud} . The $T_z = -1$ nuclei, however, are all farther from stability than the currently known cases, have unstable daughters, and exhibit multiple decay branches. Their measurement presents real experimental challenges.

The ft value that characterizes any β transition is determined by three measurable parameters: the transition energy, Q_{EC} , which is used in calculating the statistical rate function f ; the half-life of the β emitter and the branching-ratio for the transition of interest, which together yield the partial half-life, t . What separates the decay of a $T_z = -1$ superallowed emitter from one with $T_z = 0$ is the complexity of its decay. While the latter concentrates $> 99\%$ of its total decay strength in the superallowed branch, the former includes strong Gamow-Teller branches in addition to the superallowed one. To achieve the $\sim 0.1\%$ precision required for a meaningful branching-ratio result, all that is required for the latter case is to measure any nonsuperallowed branches with modest precision ($\sim 10\%$) and subtract their total from 100%; for the former case, the superallowed branch itself must be measured directly and with the full $\sim 0.1\%$ precision. With the result reported in this Letter, ^{22}Mg becomes the first case of a $T_z = -1$ parent with an unstable daughter whose branching ratio and half-life have been measured with such high precision. The techniques used in this measurement can be applied in the future to other similar decays.

A detailed description of these experiments will appear in a later publication [4]. In summary, we produced 3.9-s ^{22}Mg using a 28A-MeV ^{23}Na beam from the Texas A&M K500 cyclotron to initiate the $^1\text{H}(^{23}\text{Na}, 2n)^{22}\text{Mg}$ reaction on an LN₂-cooled hydrogen gas target. The ejectiles entered the MARS spectrometer [5] where the ^{23}Na beam was stopped and the fully stripped reaction products were spatially separated from one another, leaving a $> 99.6\%$ pure ^{22}Mg beam at the extraction slits in the MARS focal plane. This beam, containing $\sim 10^4$ atoms/s at 23A MeV, then exited the vacuum system through a

50- μm -thick Kapton window, passed successively through a 0.3-mm-thick BC-104 scintillator and a stack of aluminum degraders, finally stopping in the 75- μm -thick aluminized Mylar tape of a tape-transport system. Since the few impurities remaining in the beam had different ranges from ^{22}Mg , most were not collected on the tape; residual collected impurities were found to be substantially less than 0.1% of the ^{22}Mg content.

In a typical measurement, we collected ^{22}Mg on the tape for 5 s, then interrupted the accelerator beam in a few μs by shifting off resonance the phase of one of the cyclotron dees, and triggered the tape-transport system to move the sample in 180 ms to a shielded counting station located 90 cm away. There, data were recorded for a predetermined counting period while the beam remained off. This cycle was clock controlled and was repeated continuously. For the branching-ratio measurement, each counting period was 5 s, during which the sample was positioned between a 70% HPGe γ -ray detector and a 1-mm-thick BC404 plastic scintillator that was used to detect β^+ particles. The former was located 15 cm from the sample, while the latter was 3 mm away. Time-tagged coincidence (or singles) data were stored event by event.

For the half-life measurement, a completely different arrangement was used at the shielded counting location. In this case, the tape moved the collected sample to the center of a 4π proportional gas counter, where the β^+ particles were detected and recorded for 80 s, more than 20 half-lives of ^{22}Mg . The counter signals were amplified and sent to a fast discriminator, which triggered a gate generator. The gate signals were then multiscaled, with the scaler's channel advance being provided by a time base accurate and stable to 5 ppm. A separate decay spectrum was thus recorded for each cycle. The time duration of the nonextendable signal from the gate generator was chosen to be much longer than any dead time from the up-stream modules. This produced a well-defined dominant dead time, which was monitored continuously during the measurement and later used during analysis to correct the data cycle by cycle. Tests with 1.8-s ^{35}Ar implanted under identical conditions demonstrated no leakage of activity from the tape. A similar system has been used previously and proven effective in the measurement of very precise half-lives [6].

Branching ratio.—The decay scheme of ^{22}Mg appears in Fig. 1. Apart from the ground state of ^{22}Na —known [7] to have $(J^\pi, T) = (3^+, 0)$ —it includes the analog $(0^+, 1)$ state fed by the superallowed β transition, and two $(1^+, 0)$ states fed by Gamow-Teller branches. The β transition feeding the ground state must be second-forbidden unique and, being suppressed by some 10 orders of magnitude, can be neglected. Thus, branching ratios to the excited states can be obtained from the *relative* intensities of γ rays observed following the decay of ^{22}Mg . Figure 2 shows a portion of the spectrum of these γ rays, observed in coincidence with β^+ particles.

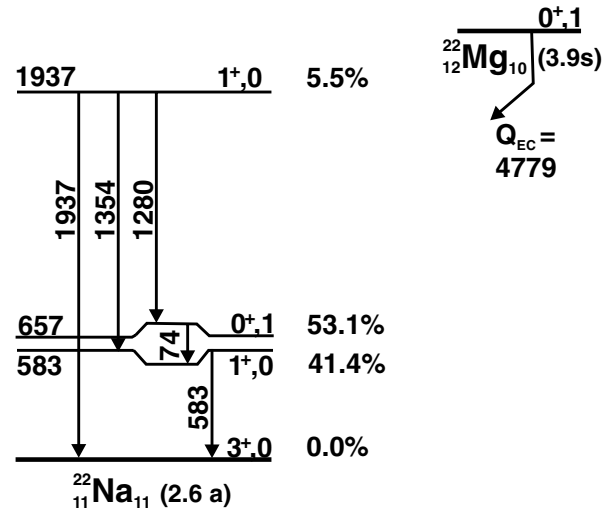


FIG. 1. Decay scheme for the β decay of ^{22}Mg .

The essence of a precise determination of the superallowed branching ratio is an equally precise measurement of the relative intensities of the 74 and 583 keV γ rays. To be sure, the intensities of the other three γ rays must be measured carefully also, but much less demanding precision is required. The primary measurement was also complicated by three factors peculiar to this decay: (i) HPGe detector signals from a low energy 74-keV γ ray have a wide range of rise times, so special care had to be taken to ensure that none were missed; (ii) the 583 keV state in ^{22}Na has a half-life of 245 ns, which required us to remeasure this half-life and to use a $2 \mu\text{s}$ β - γ coincidence timing window to minimize the correction for losses from the 583-keV peak; and (iii) the 511 + 74 keV coincident-sum peak is unresolved from the 583 keV peak, a detail that demanded special attention in analysis.

The fundamental challenge of this measurement, however, was to calibrate the efficiency of an HPGe detector

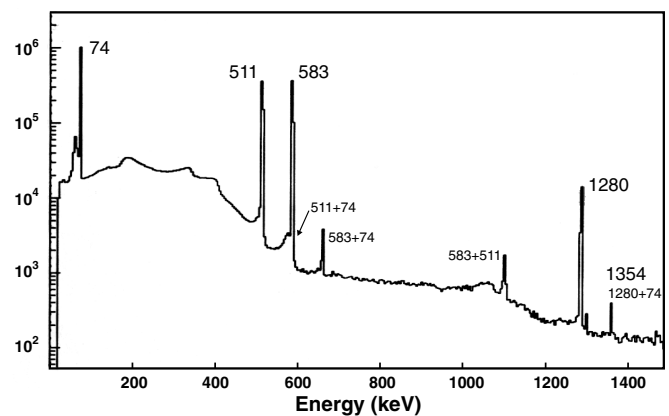


FIG. 2. Spectrum of γ rays observed in coincidence with β particles following the decay of ^{22}Mg . Primary and coincident-sum peaks are labeled in keV.

over a range from 74 to 1937 keV, with the highest possible precision between 74 and 583 keV. We took data from 13 individual sources of ten radionuclides: ^{48}Cr , ^{60}Co , ^{88}Y , ^{108m}Ag , ^{109}Cd , ^{120m}Sb , ^{133}Ba , ^{134}Cs , ^{137}Cs , and ^{180}Hf . Three of these sources we produced ourselves, ^{48}Cr and ^{120m}Sb by using the K500 cyclotron to initiate the $^1\text{H}(^{50}\text{Cr}, p2n)^{48}\text{Cr}$ and $^{120}\text{Sn}(p, n)^{120m}\text{Sb}$ reactions, respectively, and ^{180}Hf by irradiating enriched ^{179}Hf with thermal neutrons from the Texas A&M reactor. Two ^{60}Co sources were specially prepared by the Physikalisch-Technische Bundesanstalt [8] with activities certified to 0.06%. All other sources were purchased from commercial suppliers. Sources of greatest importance to a precision calibration are those exhibiting simple γ -ray cascades uncomplicated by large conversion-electron components or by any possible β side feeding. Except for the calculable effects of electron conversion, the intensities of such cascaded γ -ray transitions are unambiguously equal. In particular, the ^{22}Mg measurement depended most crucially on the following sources (and cascaded γ -ray energies in keV): ^{48}Cr (112.4, 308.3), ^{108m}Ag (433.9, 614.28, 722.9), ^{120m}Sb (89.8, 197.3, 1023.1, 1171.3), and ^{180m}Hf (215.3, 332.3). In our analyses of all spectra—those used for calibration and those taken in the ^{22}Mg measurements—we incorporated corrections for coincidence summing (always $\leq 1\%$), and included effects from angular correlation between each pair of summing γ rays.

In addition to acquiring calibration spectra, we also made a number of measurements designed to reveal the physical dimensions and location of the detector's Ge crystal in its housing. These measurements included a scan of the side of the detector with a tightly collimated ^{133}Ba source, to determine the crystal length; a pair of ^{57}Co spectra recorded at 4-cm and 20-cm source-detector distances, to locate the front surface of the crystal; and an overall x-ray picture of the crystal in its housing, to establish its exact orientation. This information was then used as input to Monte Carlo calculations performed with the electron and photon transport code CYLTRAN [9]. With only the detector's two dead layers as adjustable parameters, we achieved excellent agreement ($\chi^2/N = 0.8$) between the Monte Carlo efficiency results and our 40 measured data points between 22 and 1836 keV. With these calculations used to interpolate between measured calibration efficiencies, we determine a relative efficiency between 74 and 583 keV of 2.876(4), a precision of 0.15%. Complete calibration details appear elsewhere [10].

On-line data for the decay of ^{22}Mg were taken for four widely differing counting rates, thus providing us with the means to test for any count-rate effects in our results. No statistically significant differences in the relative γ -ray intensities were observed but, to be safe, we eliminated from consideration that quarter of the data with the highest rate. From the remaining β - γ coincident events, we next removed the effects ($< 1\%$) of γ rays detected in

the β detector and projected out γ -ray spectra that corresponded to different ranges of detected β energies. As expected, no β -energy dependence was evident in the ratio of peak areas for the 74-keV and 583-keV transitions, since both γ rays are preceded predominantly by β transitions of very similar energy. However, relative to these two γ rays, some β -energy dependence was evident in the intensities of γ rays emanating from the state at 1937 keV, which is fed by a much lower energy β -decay branch. Consequently, we used only singles γ -ray data, which is unaffected by such systematic effects, to obtain the relative intensity of the 1280-keV transition. Though the effects of room background, negligible in coincidence, had to be incorporated for the singles data, the demands for precision are not nearly so great for the 1280-keV γ ray as they are for those at 74 and 583 keV.

Our results for the relative intensities of β -delayed γ rays following the decay of ^{22}Mg are shown in the left two columns of Table I. They are generally consistent with, but much more accurate than, previous measurements [11]; the weak 1354-keV crossover transition has never been identified before. Taking account of the calculated conversion coefficient [12], $\alpha = 0.0036$, for the 74-keV M1 transition in ^{22}Na , we used these γ -ray intensities to obtain branching ratios, shown in the right two columns of the table, for the three ^{22}Mg β transitions feeding states in ^{22}Na .

Half-life.—We recorded a total of more than 54-million multiscaled decay events from the 4π β detector, comprising some 3000 collect/count cycles in a sequence of 50 individual measurements, each with a different combination of detector high-voltage, discriminator, and dominant dead-time settings. The ratio of ^{22}Mg counts to room background was $\sim 10^4$ at the beginning of each counting cycle. In addition to the 80-s counting periods used for these measurements, we also recorded decay data for a 160-s decay period to identify and characterize any possible impurities of comparable half-life. Only 22.5-s ^{21}Na was observed, with an initial activity 1.7×10^{-4} that of ^{22}Mg , and its effects were incorporated in all analyses.

The data were analyzed with two different fitting procedures to extract the half-life: (i) a maximum-likelihood fit to the sum of all dead-time corrected decay spectra; and (ii) a global fit of individual cycle spectra,

TABLE I. Measured relative intensities of β -delayed γ rays, and deduced branching ratios (as %) for the β decay of ^{22}Mg .

E_γ	I_γ	E_x (^{22}Na)	I_β
74	58.36(6)	583	41.40(13)
583	100.00(19)	657	53.15(12)
1280	5.40(7)	1937	5.45(5)
1354	0.015(3)		
1937	0.032(3)		

with a common half-life but with amplitudes and dead times correctly matched to each cycle. The second procedure contains no approximation [6] but both yielded concordant results. To further consolidate the results, both fitting procedures and all tests were repeated on a parallel set of Monte Carlo generated spectra, mimicking the trend of the real data, but with known half-life and background. The accurate retrieval of the decay parameters used in the generation of the artificial data validated the fitting procedures and the final half-life result.

No systematic experimental effects were observed, the results from all 50 individual measurements being statistically consistent with one another. A final test for any short-lived impurities was negative as well: We removed all data from the first second of the counting period in each measurement, and refitted the remainder; then we repeated the procedure, removing the first two seconds, three seconds, and so on. Within statistics, the half-life was stable against these changes also. Our final result for the ^{22}Mg half-life is 3.8755(12) s.

Q_{EC} value.—Since ^{22}Na is a long-lived nucleus, its mass excess is well known to ± 500 eV [13], and the excitation energy of its 0^+ excited state to ± 140 eV [7]. As a result, the quality of the Q_{EC} value for the superallowed transition between ^{22}Mg and ^{22}Na depends directly on how well the mass excess of ^{22}Mg is known. The most up-to-date published mass tables [13] quote a value obtained from two 30-year-old measurements of the $^{24}\text{Mg}(p, t)^{22}\text{Mg}$ Q value [14,15], neither of which has been corrected for significant changes that have occurred in their calibration-reaction Q values over the years. In one case [15], the method of calibration was complex enough that it is impossible now to update the result; in the other [14], the measurement was tied directly to the $^{16}\text{O}(p, t)^{14}\text{O}$ Q value. Incorporating the modern value [13] for that Q value to update the original $^{24}\text{Mg}(p, t)^{22}\text{Mg}$ result [14], we obtain a mass excess for ^{22}Mg of $-402(3)$ keV. This value is supported by a very recent measurement [16] of a resonance in the $^{21}\text{Na}(p, \gamma)^{22}\text{Mg}$ reaction, from which a mass excess of $-403.2(13)$ keV is inferred. These values combined yield $Q_{EC} = 4122.1(13)$ keV for the superallowed transition from ^{22}Mg .

With branching ratio and half-life results from the present measurements, together with the updated Q_{EC} value just described, we can now obtain a corrected $\mathcal{F}t$ value for the superallowed transition from ^{22}Mg . We use the structure-dependent correction term (0.50%) calculated and tabulated in Ref. [1] inserted into Eq. (6) of that reference. The result is $\mathcal{F}t = 3071(9)$ s, in excellent agreement with 3072.2(8) s, the average $\mathcal{F}t$ value for the nine well-known cases studied to date. This agreement provides important confirmation of the structure-dependent calculations [1], which are used in all cases to extract G_V . Furthermore, a mass measurement of ^{22}Mg

with sub-keV precision would reduce the $\mathcal{F}t$ value uncertainty to ± 7 s or 0.2%, thus constituting an even more demanding test. Such precision is possible today with on-line Penning-trap mass spectrometers and, considering the unfortunate history of the ^{22}Mg mass, we would urge that such a measurement be made.

We have demonstrated for the first time that a high-precision branching ratio can be measured for the superallowed transition from a $T_z = -1$ parent to an unstable daughter. Our technique is extendable to other superallowed emitters of the same type, even those with a strong ground-state branch, since we directly measure the number of collected nuclei in the counting sample and can thus determine an absolute branching ratio for each observed transition regardless of whether all are observed.

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