

## Precise half-life measurement of the superallowed $\beta^+$ emitter $^{26}\text{Si}$

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We have measured the half-life of the superallowed beta emitter  $^{26}\text{Si}$  as part of our program to test the three-generation electroweak Standard Model via the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1]. The half life, branching ratio and  $Q_{\text{EC}}$  value are the three measured parameters that define a  $\beta$ -decay  $ft$  value, and all three must be measured precisely for the  $0^+ \rightarrow 0^+$  superallowed decays that are used for the test. The precision required by this test is, in fact, very demanding, as a measurement becomes meaningful only if its precision is better than 0.1 %. Recently the  $Q_{\text{EC}}$  value for the superallowed branch in the decay of  $^{26}\text{Si}$  has been measured to 0.0025 % accuracy [2], thus taking the first step in permitting this nucleus to join the group of superallowed emitters with  $ft$  values determined precisely enough to be used for the unitarity test. It is a particularly interesting case because its isospin symmetry-breaking correction ( $\delta_{\text{C}} - \delta_{\text{NS}}$ ), though not particularly large compared to most of the well-measured cases, is more than double the size of the correction for the superallowed transition from  $^{26}\text{Al}^{\text{m}}$ , which is its mirror transition. Experimental verification of this predicted mirror asymmetry would be a valuable test of the calculations.

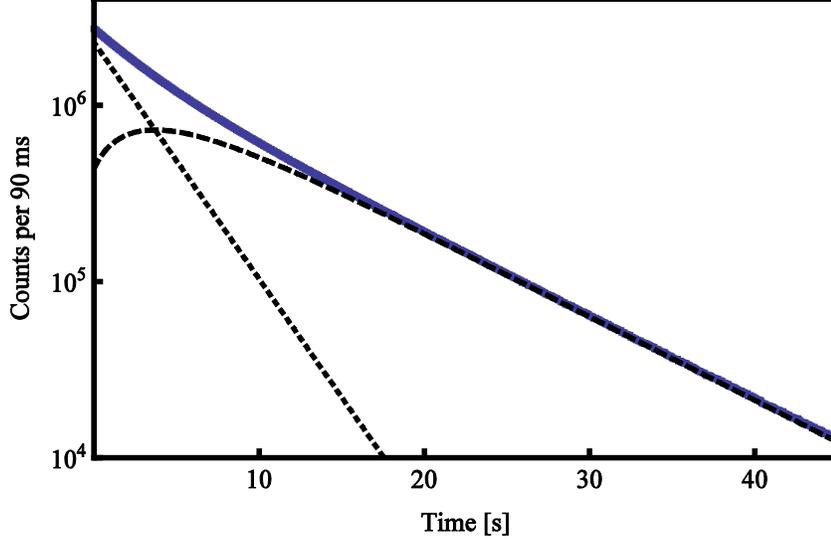
We followed essentially the same procedure we used previously in our  $^{34}\text{Ar}$  half-life experiment [3] since this case exhibits the same challenge:  $^{26}\text{Si}$  decays to a daughter,  $^{26}\text{Al}^{\text{m}}$ , which is itself radioactive with a comparable half-life. As already noted,  $^{26}\text{Al}^{\text{m}}$  is another superallowed emitter.

We produced a  $^{26}\text{Si}$  radioactive beam via the  $p(^{27}\text{Al}, 2n)^{26}\text{Si}$  reaction, with a 30 A-MeV  $^{27}\text{Al}$  primary beam impinging on a  $\text{H}_2$  cryogenic gas-target kept at a pressure of 2 atm and at liquid-nitrogen temperature. A high purity  $^{26}\text{Si}$  beam with 25.2 A MeV was then selected with the Momentum Achromat Recoil Separator (MARS) [4]. The  $^{26}\text{Si}$  beam intensity was about  $10^4$  ions per second. Similarly to the  $^{34}\text{Ar}$  half-life experiment [3], the radioactive beam was extracted into air, then passed through a thin plastic scintillator, a series of Al degraders, and eventually implanted in the 76- $\mu\text{m}$ -thick mylar tape of our fast tape-transport system. The thickness of the Al degraders was experimentally tuned to optimize the implantation and purity of the  $^{26}\text{Si}$  beam.

Data were collected in cycles: After  $^{26}\text{Si}$  nuclei had been implanted for a pre-selected time interval (of the same order as the  $^{26}\text{Si}$  half-life), the beam was turned off and the tape-transport system moved the sample in  $\sim 175$  ms to a well-shielded location 90 cm away, stopping it in the center of a  $4\pi$  proportional gas counter. The decay positrons were then detected for twenty half-lives (45 s), with signals from the detector being multiscaled into a 500-channel time spectrum. These collect-move-detect cycles were computer controlled and their timing was continuously monitored on-line. They were repeated, with a separate decay spectrum recorded for each, until the desired overall statistics had been achieved. In its shielded location, the gas counter had a background rate of about 0.5 counts/s, which was 3-4 orders of magnitude lower than the initial count rate for each collected sample.

For this experiment we accumulated data from 5,000 cycles split into 55 separate runs, which yielded a total of  $2 \times 10^8$  counts. The total time-decay spectrum obtained from the combined runs is

presented in Fig. 1, where we also show the separate contributions from the decays of the  $^{26}\text{Si}$  parent and the  $^{26}\text{Al}^m$  daughter.



**FIG. 1.** Measured time-decay spectrum (solid line) obtained for the  $\beta^+$  decay of  $^{26}\text{Si}$  and its daughter  $^{26}\text{Al}^m$ . The dotted/dashed lines represent the derived  $^{26}\text{Si}/^{26}\text{Al}^m$  contributions.

As our detection system does not disentangle the two components, the only information that can be processed is the combined parent-daughter decay. A detailed analysis of the coupled  $^{26}\text{Si}$  and  $^{26}\text{Al}^m$  decay equations gives for the total detected rate

$$\Delta_{tot} = C_1 e^{-\lambda_1 t} + C_2 e^{-\lambda_2 t}, \quad (1)$$

with

$$C_1 = N_1 \varepsilon_2 \lambda_1 \left( \frac{\varepsilon_1}{\varepsilon_2} - \frac{\lambda_2}{\lambda_1 - \lambda_2} \right) \quad (2)$$

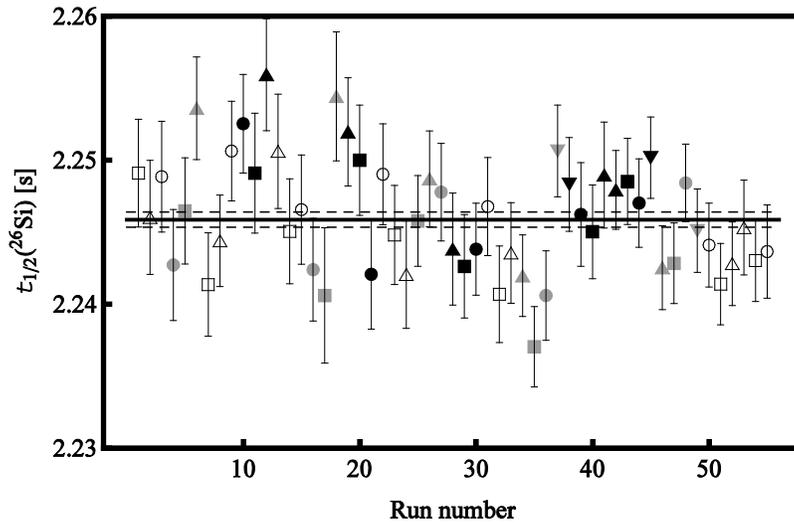
$$C_2 = N_1 \varepsilon_2 \lambda_2 \left( \frac{N_2}{N_1} + \frac{\lambda_1}{\lambda_1 - \lambda_2} \right), \quad (3)$$

where  $t$  is the time elapsed after the end of the collect period;  $N_{1,2}$  are the numbers of  $^{26}\text{Si}$  and  $^{26}\text{Al}^m$  nuclei present in the sample at  $t = 0$ ;  $\varepsilon_{1,2}$  are the experimental efficiencies for detecting the positrons from the respective decays; and  $\lambda_{1,2}$  are the corresponding decay constants. Note that if  $\varepsilon_1 = \varepsilon_2$  and  $\lambda_1 = 2\lambda_2$ , the coefficient  $C_1$  vanishes and the total decay rate is fully determined by  $C_2 e^{-\lambda_2 t}$ . While the half-lives of  $^{26}\text{Si}$  and  $^{26}\text{Al}^m$  are actually related by a factor of 2.8, this is close enough to 2 for the total decay spectrum to

be dominated by the daughter's half life. This can easily be observed in Fig. 1, where the total spectrum deviates very little from a one-component decay curve with the daughter's decay-constant. This is similar to the situation we encountered for our  $^{34}\text{Ar}$  experiment [3].

Thus, even with high accumulated statistics, the required precision can barely be obtained in a free two-component fit, which in the present case gives a half-life result for  $^{26}\text{Si}$  of 2243.2(22) ms. Much better precision can be obtained if a parent-daughter link is imposed in the fit. In this case, the two coefficients  $C_{1,2}$  are interconnected and dependent on the decay constants as shown in Eqns. 1-3. While more computation intensive, since in each iteration of the fitting process the two coefficients had to be recalculated, the effort is rewarded by a considerably improved precision. An important requirement in this linked procedure is the value of  $\varepsilon_1/\varepsilon_2$ , the relative parent/daughter detection efficiency. From a Monte Carlo analysis of our experimental setup we determined this ratio to be  $\varepsilon_1/\varepsilon_2=1.00143(25)$ .

The electronic scheme used to process the data was identical to the one used in the  $^{34}\text{Ar}$  experiment [3]. To test the robustness of our results, each run was obtained with a different combination of critical detection settings: detector bias, discriminator threshold and major dead-time combination. As seen in Fig. 2, the half-life results show no systematic dependence on detector bias or discriminator threshold.



**FIG. 2.** Test for possible systematic bias in the  $^{26}\text{Si}$  half-life measurement due to discriminator threshold or detector voltage. Open/grey/black symbols represent the three discriminator settings, 150 mV/200 mV/250 mV; the four detector biases, 2550 V, 2650 V, 2750 V and 2850 V are represented by the symbol shapes  $\Delta$ ,  $\square$ ,  $\circ$  and  $\nabla$ , respectively. The average value for the half-life is 2245.26(51) ms (statistical uncertainty only) with  $\chi^2/ndf = 70.6/54$ . The average value appears as the solid line, with dashed lines as uncertainty limits.

Although not illustrated, the results were also found to be independent of both the imposed circuit dead time and the length of time for which the sample was collected.

Further tests of the half-life stability versus undetected short-lived impurities or rate-dependent counting losses were performed by the standard “front-channel-chopping” technique, which involves

separate fits to subsets of the data with successively longer time periods removed from the beginning of the counting cycle. Here too the derived half-life proved to be stable: no statistically significant change was observed as the starting time for the fit was systematically changed.

Our new precise result for the  $^{26}\text{Si}$  half-life, 2245.3(7) ms, is considerably different from the average value quoted in the most recent survey of world data for superallowed  $0^+ \rightarrow 0^+$   $\beta$ -decay transitions [5]. However, that average is dominated by a measurement [6] that followed a somewhat similar analysis procedure to ours but neglected to deal properly with the correction for parent-daughter detection-efficiency differences.

With our half-life result for  $^{26}\text{Si}$  decay having 0.03% precision, and the  $Q_{\text{EC}}$  value for its superallowed branch being recently determined to 0.0025% [2], the  $ft$  value for the branch can in principle be determined to sub-0.1% precision once the branching ratio can be measured to that level. We plan to measure the branching ratio in the near future.

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