High-precision measurement of the $T = 1/2$ mirror β decay of ^{27}Si

A.I. Morales, G. Benzoni, A. Bracco, S. Leoni, F. Camera, O. Wieland, S. Ceruti, R. Avigo, G. Bocchi, S. Bottoni, F.C.L. Crespi, A. Giaz, L. Pellegri

Dipartimento di Fisica and INFN, Sezione di Milano, Milano, Italy.

D. Bucurescu, M. Constantin, C. Costache, D. Filipescu, I. Gheorghe, T. Glodariu, N. Marginean, R. Marginean, R. Mihai, S. Nae, A. Negret, A. Olacel, S. Pascu, L. Stroe, T. Sava, G. Suliman, R. Suvaila, S. Toma, A. Turturica

Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania.

S. Pietri

GSI, Planckstrasse 1, D-64291 Darmstadt, Germany.

Spokespersons: A.I. Morales and G. Benzoni

Local contacts: S. Toma and A. Negret

Superallowed Ft values between $T = 1/2$ isospin doublets are used since a short time ago as an alternative experimental source to extract V_{ud}, the up-down quark-mixing element of the Cabibbo-Kobayashi-Maskawa matrix. Since the precision achieved in such measurements is still one order of magnitude worst than that of superallowed Fermi $0^+ \rightarrow 0^+$ transitions, further efforts are required in order to test the conserved vector current hypothesis from this new experimental source. Based on this, the present proposal aims at performing a high-precision measurement of the β half-life and the superallowed branching ratio of the $T = 1/2$ mirror nucleus ^{27}Si, by exploiting the decay station of the IFIN-HH in Romania.

I. PHYSICS CASE

The unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix is one of the core concepts of the Electroweak Standard Model [1]. Any violation in this unitarity condition would open a new era of physics beyond the Standard Model involving contributions from exotic couplings to right-handed currents. Though there is no evidence for this up to now, increasingly high-precision measurements of the CKM matrix elements are required in order to set the limits on the possible supplementary physics. Typical tests involve nuclear superallowed $0^+ \rightarrow 0^+$ pure Fermi transitions, neutron decay, and pion β decay [2].

Superallowed β decay between nuclear states with $(J^\pi, T) = (0^+, 1)$ provides up to now the most precise value of the up-down quark-mixing element of the CKM matrix, V_{ud}. V_{ud} is directly extracted from the ratio between the vector coupling constant for a semileptonic weak process, G_V, and the fundamental weak interaction coupling constant for purely leptonic muon decay, G_F ($V_{ud} = G_V/G_F$). Here the Conserved Vector Current (CVC) hypothesis is assumed: G_V is a fundamental constant independent of the nuclear interaction, and consequently, the strength – or $f_V t$ value – of $0^+ \rightarrow 0^+$ β transitions, which are mediated only by the vector current, remains the same for all nuclei. Experimentally, the $f_V t$ value is determined from the total transition energy, Q_{EC}, and the partial half-life of the β transition, t. The former is required to determine the statistical rate function f_V, whereas the last is deduced from the β half-life of the mother state and the branching ratio (BR) of the superallowed transition. In practice, superallowed $f_V t$ values are affected by residual transition-to-transition variations arising from small radiative and isospin-symmetry breaking effects in the nuclear medium. These are accounted for by introducing a *corrected* strength, the so-called Ft value:

$$Ft = f_V t(1 + \delta'_R)(1 + \delta^V_{NS} - \delta^V_C) = \frac{K}{2G^2_V(1 + \Delta^V_R)} \tag{1}$$

The terms on the right-hand side of this expression are the transition-independent radiative correction Δ^V_R, which is the same for all semileptonic processes, a factor 2 arising from the square of the Fermi matrix element $|M_F|^2$, and fundamental constants. The terms on the left-hand side, instead, depend on the specific β transition: δ'_R and δ^V_{NS} are the transition-dependent and structure-dependent parts of the radiative correction, and δ^V_C is the nuclear structure correction due to the isospin-symmetry breaking in the mother and daughter nuclear states. Therefore the Ft value – and not $f_V t$ – is invariant under the CVC hypothesis for all pure Fermi decays.

In the last years, superallowed mixed transitions between $T = 1/2$ mirror nuclei have also been used to obtain new and complementary data for the extraction of V_{ud} [3–6]. Since the decay between isospin doublets has mixed Fermi and Gamow-Teller character, the Ft value between mirror transitions is written as [3]:

$$Ft^{mirror} = f_V t(1 + \delta'_R)(1 + \delta^V_{NS} - \delta^V_C) = \frac{2Ft}{\left(1 + \frac{f_A}{f_V}\rho^2\right)} \tag{2}$$

where f_V and f_A are the vector and axial-vector statistical rate functions, respectively, and ρ is the mixing ratio between the Gamow-Teller and Fermi contributions [3]:

$$\rho \simeq \frac{C_A M^0_{GT}}{C_V M^0_F} \tag{3}$$

with M_F and M_{GT} the Fermi and Gamow-Teller matrix elements, respectively, and C_V and C_A the strengths of the weak vector and axial-vector interactions.

It is worth noting that the precision achieved for the determination of V_{ud} from superallowed mixed mirror transitions is one order of magnitude worst than for pure Fermi decays [7]. On the one hand, this is because an additional parameter must be determined experimentally to extract the mixing ratio, and the corresponding uncertainty has to be included in the final V_{ud} value. On the other hand, most of the reported β decay data between isospin doublets were measured more than 30 years ago [3] and only a few high-precision measurements on Ft^{mirror} values (namely ^{19}Ne, ^{21}Na, ^{29}P, ^{35}Ar and ^{37}K) have been revisited since then [5–7]. So, further experiments exploiting modern equipment and analysis techniques are necessary to improve the sensitivity in the determination of V_{ud} from $T = 1/2$ isospin doublets.

In the present proposal, we aim at investigating the $T = 1/2$ mirror β decay of the nucleus ^{27}Si. At present, there is disagreement between the lifetime and BR values reported in the literature, with average scale factors S − the root square of the reduced χ^2 − of 6.0 and 2.8, repectively [3]. Since these are the largest deviations among the $T = 1/2$ mirror nuclei, our purpose is to bring the aforementioned contributions to better than one part in a thousand, thus providing a new independent measurement for the evaluation of the Ft^{mirror} value.

II. EXPERIMENTAL DETAILS

In Table I we provide the averaged half-life and superallowed branching ratio of ^{27}Si. These values have been extracted from the last survey for isospin $T = 1/2$ mirror β transitions [3]. For the aim of completion, Table II lists the γ-ray energies, parent states, and absolute γ-ray intensities reported in the ENSDF nuclear data base for this nucleus [8].

TABLE I: Half-life and superallowed BR of ^{27}Si. The scale factor S for each value is shown in the adjacent columns.

$t_{1/2}$ (s)	S	BR (%)	S
4.135(19)	6.0	99.818(22)	2.8

TABLE II: γ-ray energies, parent states, and absolute γ-ray intensities for ^{27}Si.

E_γ (keV)	E_{level} (keV)	I_γ (%)
170.82(10)	1014.54	≈ 0.009
843.76(10)	843.77	< 0.004
1014.52(10)	1014.54	≈ 0.02
1720.3(8)	2734.9	≈ 0.013
2212.01(10)	2212.11	0.180(13)
2734.7(8)	2734.9	≈ 0.004
2982.00(5)	2982.18	0.026(13)
3004.0(9)	3004.2	< 0.001

The nuclei of ^{27}Si will be produced in a ^{24}Mg$(\alpha, n)^{27}$Si reaction with an incident beam energy of ~ 17.5 MeV. This is the optimal energy to maximize the total cross section of ^{27}Si to ~ 90 mb, as shown in the left panel of Fig. 1, where

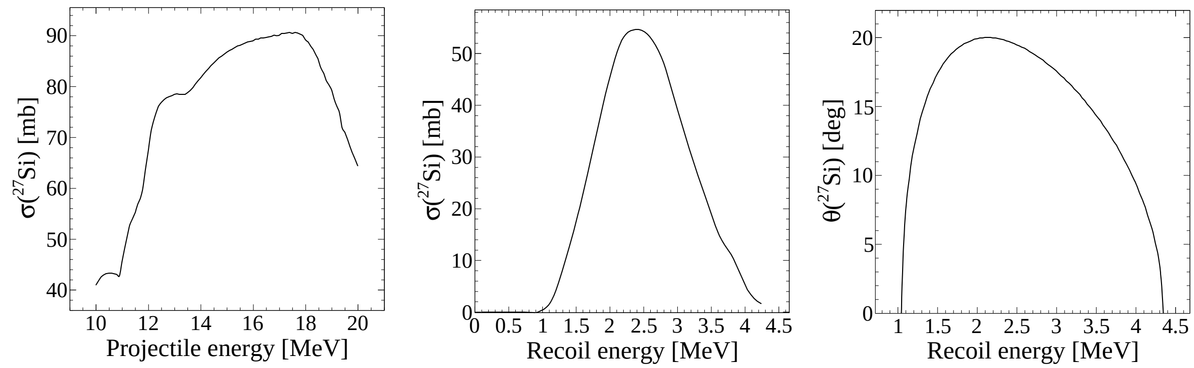

FIG. 1: Left: Total cross sections for the reaction ^{24}Mg$(\alpha, n)^{27}$Si as a function of the incident beam energy, calculated with the code TALYS. Centre: ^{27}Si cross section as a function of the recoil energy. Right: Angular distribution of ^{27}Si nuclei as a function of the recoil energy. The last two figures correspond to an incident beam energy of 17.5 MeV.

the excitation function of the reaction is drawn. The middle and right panels show, respectively, the cross section and angular distribution of ^{27}Si as a function of the recoil energy for an incident beam energy of 17.5 MeV. Considering Fig. 1, and according to LISE++ calculations, we estimate an optimal target thickness of $\sim$ 300 $\mu g/cm^2$ in order to implant the nuclei in the kapton tape, with implantation depths ranging between 0.2 and 3.4 μm. These estimates have been made taking into account that the vacuum in the reaction chamber is of the order of 1×10^{-6} mbar, and selecting two extreme cases: The first corresponds to ^{27}Si nuclei produced in the first layer of the target with energies of 1.5 MeV, and the second to 3.5 MeV ^{27}Si recoils placed in the last layer of the target. The nuclei implanted in the kapton tape will then be transported from the reaction chamber to the β-decay spectroscopy setup, traversing a distance of about 3.5 m with a 1.5 m thick wall between the two experimental halls, acting as a shielding. The transportation time is less than 1 s. At the measurement point, 3 EUROBALL-type Ge clover detectors with BGO suppression shield will be mounted for β-delayed γ-ray spectroscopic studies. These can also be used to measure the 511-keV γ rays emitted in the anihilation of the β positrons if a plastic scintillator is not available for the detection of the β particles.

In high-precision β-decay experiments, all systematic errors must be accurately evaluated. These arise mainly from radioactive reaction contaminants and rate-dependent systematic effects, such as dead time and pileup. Standard procedures to evaluate the impact of contaminant activity consist in varying the beam-on/beam-off cycling times to maximize their effect on the measured half-lives. For the rate-dependent systematic effects, individual settings with different amplifier shaping times and DAQ periods are collected. For the BR measurement, a very precise determination of the absolute γ-ray detection efficiency is necessary.

The contaminant nuclei produced in the ^{24}Mg$(\alpha, n)^{27}$Si reaction are listed in table III together with the half-lives and the total cross sections calculated with the code TALYS. All species are stable except ^{26}Al, which has two β-decaying states. The cross section of the 5^+ ground state is a factor 12 smaller than that of ^{27}Si. This, together with the much larger half-life, $7.17 \times 10^5(24)$ y, translates into a separable contamination in the activity curve of ^{27}Si. Instead, the half-life of the 0^+ isomeric state, 6.3464(7) s, is similar to that of ^{27}Si, but the production yields are a factor $\sim$ 800 smaller. As mentioned above, the corresponding contributions will be evaluated by using two accumulation/decay time cycles. The first will consist of 8 s implantation periods followed by 16 s decay times, while the second will consist of 8s-128s beam-on/beam-off periods in order to determine the concentration of the main contaminant, ^{26}Al^{gs}. As an illustration, we show in Fig. 2 the concentrations of implanted ^{27}Si (solid line), ^{26}Al^{gs} (dashed line), and ^{26}Al^{m} (red line) for the time-cycle settings proposed.

III. EXPECTED YIELDS

In total, we expect to produce 2.1×10^6 nuclei of ^{27}Si per second for a beam intensity of 500 nA. Nuclei with angles between 5-15^o will more likely be stopped in the beam plug, so approximately 75% of the isotopes will be collected in the kapton tape and will be delivered to the three-clover set up. Thus, for periods of 8 s we will accumulate $\sim$ 3.3×10^6 nuclei, of which $\sim 2.7 \times 10^6$ will β decay in the measurement point. Considering an efficiency for the β-decay γ-ray setup of 1% and an absolute γ-ray intensity of less than 0.004% for the 843.76(9)-keV γ peak, which is one of the worst-case scenarios [8], we expect to observe a maximum of $\sim 3.8 \times 10^3$ γ rays per day deexciting this state. These estimations are based on calculated cross sections, and therefore, the yields provided are illustrative and are to

TABLE III: Contaminant species produced in the reaction ^{24}Mg$(\alpha, n)^{27}$Si. The total cross sections, calculated with the code TALYS, are shown in the second column. In the last column the experimental β half-lives extracted from the ENSDF data base are shown.

Nucleus	σ (mb)	$t_{1/2}$
^{28}Si	0.002	stable
^{27}Al	383	stable
^{26}Al^{gs}	7.27	$7.17 \times 10^5(24)$ y
^{26}Al^{m}	0.114	6.3464(7) s
^{26}Mg	93	stable
^{24}Mg	464	stable
^{23}Na	0.13	stable
^{20}Ne	2.28	stable

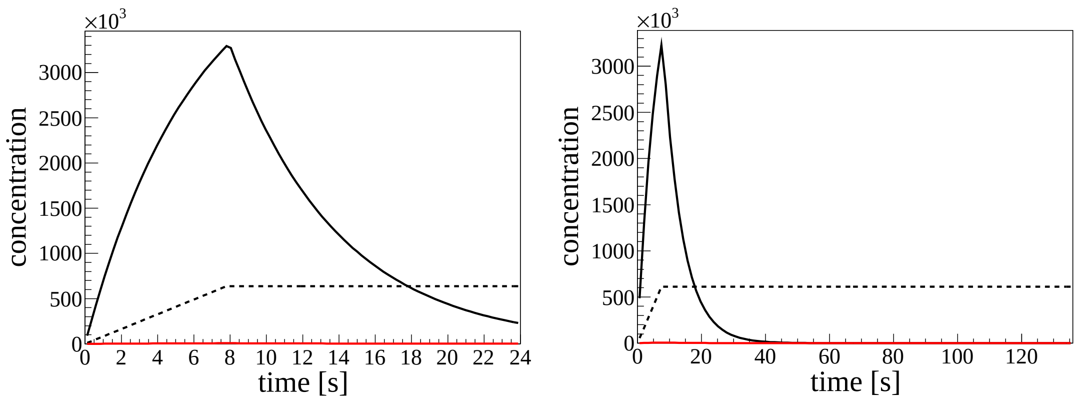

FIG. 2: Left: Concentrations of ^{27}Si (solid line), ^{26}Al^{gs} (dashed line), and ^{26}Al^{m} (red line) for the 8s-16s time cycle. Right: Same as left panel for a 64s-128s time cycle.

be optimized in the near future.

IV. SUMMARY

It is worth noting that the present proposal represents a challenge for the IFIN-HH, since it would be one of the first experiments aiming at exploiting the recently comissioned β-decay station of Bucharest.

Given the exploratory character of this experiment, we propose to split it into two parts: In the former, our aim will be measuring the half-life of ^{27}Si with a precision better than one part in a thousand. Concurrently, we will investigate the performance of the setup for the feasibility of the high-precision measurement of the BR. During this initial run, different accumulation and electronic settings will be performed for the high-precision measurement of the β-decay half-life of ^{27}Si. Then, if the experimental conditions are suitable for the measurement of the BR, we will request additional days since this second measurement will require higher statistics.

In summary, we request **15 shifts** for the measurement of the half-life of ^{27}Si and **3 additional shifts** for the optimization of the experimental setup.

[1] J. C. Hardy and S. Towner, Ann. Phys. **525**, 443 (2013).
[2] N. Severijns and O. Naviliat-Cuncic, Ann. Rev. Nucl. Part. Sci. **61**, 23 (2011).
[3] N. Severijns, M. Tandecki, T. Phalet, and I. Towner, Phys. Rev. C **78**, 055501 (2008).
[4] W. Satula, J. Dobaczewski, W. Nazarewicz, and T. R. Werner, Phys. Rev. C **86**, 054316 (2012).
[5] A. Bacquias et al., Eur. Phys. J. A **48**, 155 (2012).
[6] L. J. Broussard et al., Phys. Rev. Lett. **112**, 212301 (2014).
[7] O. Naviliat-Cuncic and N. Severijns, Phys. Rev. Lett. **102**, 142302 (2009).
[8] M. S. Basunia, Nuclear Data Sheets **112**, 1875 (2011).