Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Measurement of the super-allowed branching ratio of $^{10}\text{C}$

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Beam time requested: 21 shifts on LA1

Abstract

We propose to measure the super-allowed branching ratio of $^{10}\text{C}$, the lightest of all nuclei decaying by a $0^+ \rightarrow 0^+$ transition. The light nuclei have a much stronger impact on limits of physics beyond the standard model than heavier nuclei. We propose a measurement which should reach a precision similar to the two latest measurements, however, with a different method employing a precisely efficiency calibrated germanium detector. As no method exists to greatly improve on previous results, the branching ratio has to be measured with independent methods.

1 Introduction

Super-allowed $0^+ \rightarrow 0^+$ $\beta$ decays are compelling because of their simplicity. The axial-vector decay strength is zero for such decays, so the measured $F_t$ values are directly related to the weak vector coupling constant through the following equation [1]:

$$F_t = ft(1 + \delta_R')(1 + \delta_{NS} - \delta_c') = \frac{K}{(M_F^2 \ast G'v^2)}$$  \hspace{1cm} (1)

where $K$ is a known constant, $G'v^2$ is the effective vector coupling constant and $M_F$ is the Fermi matrix element between analogue states. Radiative corrections, $\delta_R'$ modify the decay rate by about 1.5% and structure-dependent corrections $\delta_{NS} - \delta_c'$ modify the "pure" Fermi matrix element by about 0.5-1%. Figure 1 shows these $F_t$ values for the 14 most precisely measured values.

Accurate experimental data on $Q_{EC}$-values, half-lives and branching ratios combined with the three correction terms permit precise tests of the Conserved Vector Current (CVC) hypothesis, via the constancy of $F_t$ values, irrespective of the $0^+ \rightarrow 0^+$ decay studied [1]. The CVC test achieved through these nuclear physics experiments is currently far superior to any
particle physics tests [1, 2]. At present, the best hopes for further improvements are also in the field of super-allowed $\beta$ decay.

These data also yield a value for $G'_\nu$ which, in combination with the weak vector coupling constant for the purely leptonic muon decay, provides a value for $V_{ud}$, the up-down element of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix. Together with the smaller elements, $V_{us}$ and $V_{ub}$, this matrix element provides a stringent test of the unitarity of the CKM matrix yielding $\sum V_{ux}^2 = 0.99956(49)$.

These very precise data allow also searching for physics beyond the presently adopted standard model of the electro-weak interaction. From a theoretical point of view, the super-allowed Fermi transition could be a mixture of the dominant vector current and a small contribution of a scalar current. Current limits of scalar currents are [2]:

$$b_F = \text{Re}( (C_s + C'_s) / C_v ) = 0.0026(42) \quad (90\% \text{ CL})$$

with the $C_x$’s being the scalar and vector coupling constants ($C'_x = C_x$, if time reversal symmetry holds and parity is maximally violated). Hardy and Towner [1] determined a similar quantity only from the super-allowed $0^+ \rightarrow 0^+$ decays alone as $|C_s| / |C_v| \leq 0.065$ and $|C'_s| / |C_v| \leq 0.065$ demonstrating the influence of these measurements have.

The same authors also showed the influence in particular of the $0^+ \rightarrow 0^+$ decays of the light nuclei. Figure 2 clearly demonstrates that an improvement of the Ft values of $^{10}$C and $^{14}$O would help putting more stringent limits on exotic couplings with nuclear $\beta$ decay.

**Figure 1:** Ft value as compiled by Hardy and Towner [1] completed with recent results.

**Figure 2:** Corrected Ft values plotted as a function of the charge on the daughter nucleus, Z. The curved lines represent the approximate loci the Ft values would follow if a scalar current existed with $b_F = \pm0.004$ (from [1]).
This clearly indicates that improvements for the lightest nuclei are highly desirable. Figure 3 shows the error budget for $^{10}$C, the target nucleus of the present proposal. The branching ratio for the super-allowed transition has by far the largest contribution to the total uncertainty. Therefore, the aim of the present proposal is to improve on the error bar of the branching ratio of $^{10}$C.

## 2 Proposed experiment

In the present proposal, we would like to measure the $\beta$-decay branching ratios with a precision between 0.1% and 0.15%. The decay scheme of $^{10}$C (figure 4) shows the particularities of this decay: one of the $\gamma$ rays has an energy of 1021.7 keV, almost exactly twice the energy of the annihilation quanta of the positrons emitted in the decay of $^{10}$C. Therefore, the main difficulty of the present experiment will be to determine the pile-up contribution to the information of interest, the branching ratio of the 1021.7 keV $\gamma$ ray.

![Figure 3: Error budget of $^{10}$C. The branching ratio is by far the largest contributor to the total uncertainty. A new measurement of the half-life [3] with a preliminary precision of about 0.01% is not yet included in these data.](image)

The two most precise measurements [4,5] produced $^{10}$C by a (p,n) reaction on an enriched $^{10}$B target (beam-on and beam-off cycles). The branching ratio is the ratio of the number of (efficiency corrected) counts $N$ in the $\gamma$-ray peaks at 1022 keV and at 718 keV (see figure 4, left):

$$BR = \frac{N(1022)}{N(718)} = \frac{Y(1022)}{Y(718)} \times \frac{\varepsilon(718)}{\varepsilon(1022)}$$

where $Y$ is the measured yield and $\varepsilon$ is the efficiency, at the energies given in parentheses, respectively. The efficiency ratio was determined by in-beam measurements on a $^{10}$B target ($^{10}$B(p,p')$^{10}$B) of the $\gamma$-ray ratio between a first $\gamma$ ray at 414 keV and the $\gamma$ rays of interest (see figure 4, right). In this case, no absolute efficiency is needed, but only the relative efficiencies between a 1022 keV $\gamma$ ray and a 718 keV $\gamma$ ray.

The branching ratios thus determined were 1.4625(25)% [4], a precision of 0.17%, and 1.4665(38)% [5], a precision of 0.26%.

With our efficiency calibrated germanium detector [6], we can perform a similar measurement, except that we do not need the relative efficiency measurement, because we know the relative efficiency of our detector with a precision of 0.1%. Therefore, a $\gamma$ singles measurement yields directly the branching ratio searched for.

We can use different approaches to determine the 511 pile-up contribution:
i) we will measure the pile-up contribution by means of the decay of $^{19}\text{Ne}$, a $\beta^+$ emitter with a similar half-life (17.3 s) and a $Q_{\text{EC}}$ (3238 keV) value close to $^{10}\text{C}$. In this case no $\gamma$ ray at 1022 keV exists and all counts in this peak arise from pile-up.

ii) by cutting the beginning of the time distribution off-line, we will modify the contribution of pile-up events, because the pile-up of two 511 keV $\gamma$ rays depends differently on the counting rate as the rate of the 1021.7 keV $\gamma$ ray.

iii) we will at least perform measurements at 2 different distances from the source using thus the fact that the detection efficiency of a single $\gamma$ ray will decrease with the distance as $r^2$, whereas the efficiency for a pile-up event will vary as $r^4$.

iv) we will perform measurements with absorbers between the source and the germanium detector. These absorbers will decrease the flux of 511 keV quanta more than the one of a single 1021.7 keV $\gamma$ ray.

Out of these four different possibilities we will use certainly the first two. As for the other two, this depends on the rate we will have and the statistics accumulated.

Figure 4: $^{10}\text{C}$ decay scheme (left) and in-beam decay of the 2.154 MeV state populated in a $(p,p')$ reaction on the same target.

3 Experimental setup and experiment

The branching ratio will be measured by means of our precisely calibrated germanium detector [6]. The activity will be accumulated on a fixed catcher with a slight angle such that the catcher faces the germanium detector at 0°. The germanium detector has been calibrated in efficiency with a relative precision of 0.1% in the region of energy interesting in the present proposal, however, at a fixed distance of 15 cm and with no additional matter in between the source and the detector, two principles we will possibly violate to some extent here (option iii) and iv) above). However, we believe that the modified distance (e.g. 20 cm instead of 15 cm) and the matter added (e.g. 2 cm of aluminum) should only change marginally the
precision on the efficiency of our detector. Off-line measurements will be performed and compared to simulations to verify this point.

The measurements will be performed in continuous mode. Each time a proton pulse is available, we will take it. This is possible, as we need to measure only the relative branching ratio between the 1021.7 keV $\gamma$ ray and the 718 keV $\gamma$ ray, the latter representing 100% of all decays. The experiment trigger would thus be the trigger of the germanium detector.

4 Statistics and measurement times

We aim here at a precision of the super-allowed branch of 0.15 % or better, a precision comparable to the present world average. For this purpose, we need to detect about $10^6$ $\gamma$ rays of the 1022 keV ray which yields then a statistical uncertainty of the order of 0.1%. Together with the uncertainty of the germanium efficiency (0.1%) we should obtain a total uncertainty of the order of 0.15%.

If we accumulate $5 \times 10^5$ $^{10}$C per proton pulse, the number of $1022$ keV $\gamma$ rays observed per proton pulse is as follows:

$$I_{1021.7} = 5 \times 10^5 \text{ }^{10}\text{C} / \text{proton pulse} \times 0.0146 \text{ (1021.7 keV branching ratio)} \times 0.0028 \text{ (}\gamma\text{ eff.)} = 20 \text{ }\gamma\text{ / proton pulse.}$$

If we get 15 proton pulses per minute, we can get about 300 $\gamma$ rays per minute, yielding a total of 18000/h. After about three days (20h each) of beam time we would reach the required number of counts in the 1021.7 keV peak of about $10^6$.

The pile-up contribution due to two 511 keV $\gamma$ quanta was estimated by means of a Monte-Carlo simulation. For $5 \times 10^5$ $^{10}$C per proton pulse, we have $10^6$ 511 $\gamma$ rays. The efficiency for the 511 keV annihilation quanta is difficult to estimate, because only half of the positrons will annihilate in the catcher, the other half annihilating somewhere in the surrounding material. We assume an efficiency of 0.4% and a pile-up window of 2 $\mu$s (shaping time of the germanium signals). We thus obtain about 1.5% of the 1022 keV peak to be due to pile-up of two 511 keV $\gamma$ quanta. We have to determine this correction with a precision of a few percent.

For $^{19}$Ne, we can expect about $10^7$ ions per proton pulse. However, we will vary the number of $^{19}$Ne between $5 \times 10^5$ per proton pulse (like $^{10}$C) and the maximum rate in order to compare the pile-up rate as a function of the total number of $^{19}$Ne accumulated. We estimate that we need about one day for this measurement. With a rate of 20 $\gamma$ / proton pulse from above and a pile-up percentage of 1.5%, we obtain 5400 511keV-511keV pile-up events allowing us to determine the pile-up probability with an error of 1-2%.

Two more days will be used to perform measurements at a different distance or with an absorber between the source and the germanium detector. In addition, we need about one day to start the experiment, to optimize the settings of the separator and of our setup.
5 Beam time request

A total of 7 days is requested for the present proposal. It decomposes as follows:

- starting the experiment, setting our separator and experimental setup:      1 day
- measurement with $^{10}$C in optimum conditions:                        3 days
- measurement with $^{19}$Ne:                                           1 day
- $^{10}$C measurement with either an absorber or at a different position:  2 days

References

[3] G.F. Grinyer, private communication
Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: one germanium detector at LA1

<table>
<thead>
<tr>
<th>Part of the experiment/equipment</th>
<th>Availability</th>
<th>Design and manufacturing</th>
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</thead>
<tbody>
<tr>
<td>[if relevant, name fixed ISOLDE installation: COLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH]</td>
<td>☑ Existing</td>
<td>☑ To be used without any modification</td>
</tr>
<tr>
<td>[Part 1 of experiment/equipment]</td>
<td>☑ Existing</td>
<td>☑ To be used without any modification</td>
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<tr>
<td>One HP germanium detector</td>
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<td>☑ To be modified</td>
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<tr>
<td></td>
<td>☑ Standard equipment supplied by a manufacturer</td>
<td>☑ CERN/collaboration responsible for the design and/or manufacturing</td>
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HAZARDS GENERATED BY THE EXPERIMENT

Hazards named in the document relevant for the fixed installation.

Additional hazards:

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<th>Hazards</th>
<th>[Part 1 of the experiment/equipment]</th>
<th>[Part 2 of the experiment/equipment]</th>
<th>[Part 3 of the experiment/equipment]</th>
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<td>Magnetic field</td>
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<td>Batteries</td>
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<td>Capacitors</td>
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<tr>
<td>Ionizing radiation</td>
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<tr>
<td>Target material</td>
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<tr>
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<td>• Open source</td>
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<td>• Sealed source (ISO standard)</td>
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<td>• Isotope</td>
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<tr>
<td>• Activity</td>
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### Use of activated material:

- **Description**
- **Dose rate on contact and in 10 cm distance**
- **Isotope**
- **Activity**

### Non-ionizing radiation

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<tr>
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<td>Radiofrequency (1-300MHz)</td>
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### Chemical

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<td>(chemical agent), (quantity)</td>
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<td>Irritant</td>
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<td>Flammable</td>
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<td>environment</td>
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### Mechanical

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<td>Mechanical properties (Sharp, rough, slippery)</td>
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<tr>
<td>Vibration</td>
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<tr>
<td>Vehicles and Means of Transport</td>
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### Noise

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<th>[frequency],[Hz]</th>
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### Physical

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<tr>
<td>Access to high workplaces</td>
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<tr>
<td>Obstructions in passageways</td>
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<td>Manual handling</td>
<td>[location]</td>
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<tr>
<td>Poor ergonomics</td>
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### Hazard identification

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): *(make a rough estimate of the total power consumption of the additional equipment used in the experiment)*

**10 A, 220V**