EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

High-precision branching ratio measurement for the superallowed Fermi β emitter ^{18}Ne

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Abstract: The study of superallowed Fermi β transitions between nuclear isobaric analogue states of spin-parity $J^{\pi} = 0^{+}$ provides demanding, and fundamental, tests of the properties of the electroweak interaction. These studies, which include some 200+ individual measurements, have been used to test the conserved-vector-current hypothesis, set limits on weak scalar currents, test the unitarity of the Cabibbo-Kobayashi-Maskawa quark mixing matrix, and set limits on physics beyond the Standard Model. The case of the $T_Z = -1$ superallowed Fermi β emitter ^{18}Ne provides an excellent candidate to help constrain theoretical corrections that are applied to the entire set of superallowed emitters. In particular, the isospin symmetry breaking correction δ_C predicted by different theoretical models exhibit large variations, ranging from 0.27% to 1.41%. However, an improvement in the branching ratio to the isobaric analogue state is required, and the present experiment proposes to improve precision of the branching ratio to 0.3%.

Requested protons: 14 shifts
Experimental Area: LA1

1 Motivation

The study of superallowed Fermi β transitions between nuclear isobaric analog states (IAS) of spin $J^\pi = 0^+$ provides demanding, and fundamental, tests of the properties of the electroweak interaction. In particular, high-precision measurements of the β decay ft values for superallowed Fermi β emitters with isospin $T = 1$ have been used to validate the conserved vector current (CVC) hypothesis to better than 12 parts in 10^5 and provide the most precise determination of V_{ud}, by far the most precisely determined element of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [1–4]. Experimental measurements of these β decay ft values requires high-precision determinations for the Q-value (to $< 0.02\%$), half-life (to $< 0.03\%$), and branching ratio to the isobaric analogue state (to $< 0.3\%$).

The experimentally measured ft values must be modified by several small ($\sim$ 1–2%) theoretical corrections for Coulomb and radiative effects and these corrected ft values, denoted $\mathcal{F}t$, are expected to be nucleus independent for all $0^+ \to 0^+$ decays. The $\mathcal{F}t$ value is defined as:

$$\mathcal{F}t = ft(1 + \delta'_R)(1 + \delta_{NS} - \delta_C) = \frac{K}{2G_V^2(1 + \Delta_R^V)} \tag{1}$$

where K is a collection of known constants, G_V is the vector coupling constant, δ'_R and δ_{NS} are nucleus-dependent radiative corrections, δ_C is the isospin symmetry breaking correction, and Δ_R^V is the transition-independent radiative correction.

Current interest lies in the set of superallowed decays with $T_Z = -1$ parents, as the δ_C corrections are almost always larger than those for the $T_Z = 0$ parents of the same mass. This arises naturally due to the larger difference in proton and neutron separation energies that serves to increase the radial-overlap mismatch between the proton and neutron wave functions in the parent and daughter nuclei. However, high-precision measurements of the ft values for these decays are more challenging than for the $T_Z = 0$ parents, due both to the fact that they are further from stability, where production of beams becomes more difficult, and their daughter nuclei are, in general, also β unstable and give rise to unwanted, but unavoidable, time-dependent β-decay backgrounds. In addition, for most of the $T_Z = -1$ parent decays there are strong Gamow-Teller feedings to low-lying $J^\pi = 1^+$ states in the odd-odd $N = Z$ daughter nuclei that compete with the superallowed transitions making the superallowed branching ratios difficult to measure precisely. These experimental challenges are evidenced by the absence of high-precision ft values for the majority of the $T_Z = -1$ emitters beyond ^{10}C and ^{14}O, for which the daughter nuclei are stable, as can be seen in Figure 1. Recent experimental efforts, in combination with extensive simulation work, have, however, demonstrated that these challenges can be overcome [5–10]. Within our collaboration, we are actively pursuing to improve the ft values for all $T_Z = -1$ superallowed emitters, including four of least precisely measured cases of ^{22}Mg (experiment IS614 accepted at ISOLDE), ^{26}Si (proposal accepted at JYFL), ^{30}S (proposal accepted at GANIL/LISE), and ^{18}Ne.

The specific case of the superallowed decay of the $T_Z = -1$ parent ^{18}Ne provides an excellent candidate for investigating the theoretical description of isospin symmetry breaking as the δ_C correction is particularly sensitive to the model employed with values

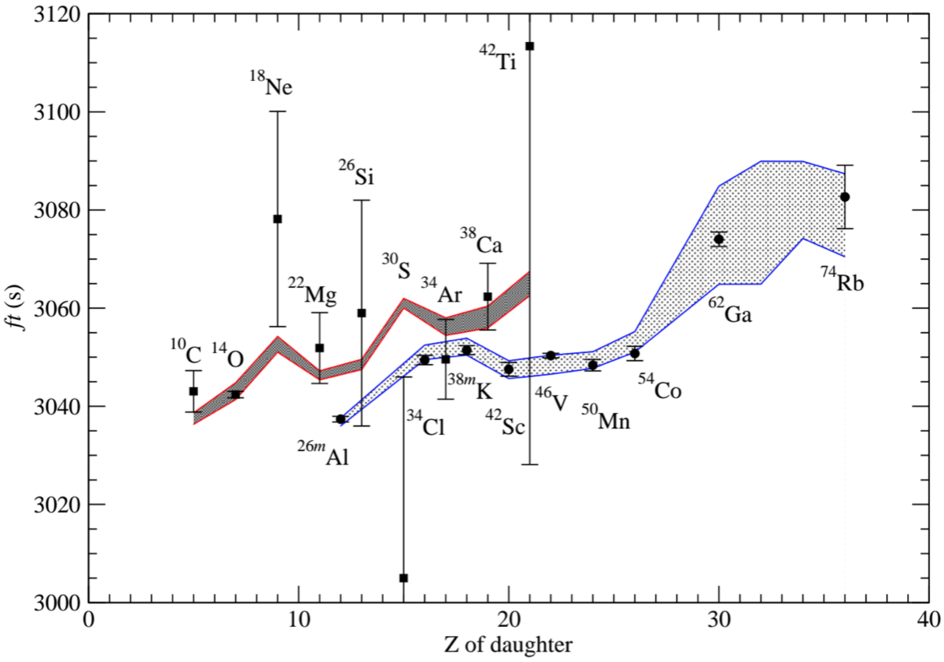

Figure 1: The experimentally measured ft values for the $T = 1$ superallowed Fermi β emitters. Both bands represent the quantity $\mathcal{F}t/[(1 + \delta_R)(1\delta_C + \delta_{NS})]$. The two separate bands distinguish those β emitters whose parent nuclei have isospin $T_Z = -1$ (darker shading, squares) from those with $T_Z = 0$ (lighter shading, circles). Adopted from Fig. 9 of Ref. [4] and updated.

ranging from 0.27% to 1.41% [1,11–14] as is shown in Figure 2. Presently, the standard in this field is set by the δ_C calculations of Towner and Hardy, with radial wave functions calculated using a Woods-Saxon potential constrained to experimental binding energies and nuclear charge radii [11]. These calculations yield a value of $\delta_{C2}(^{18}\text{Ne}) = 0.405(25)\%$ [1] for the radial overlap component of isospin symmetry breaking but when evaluated using Hartree-Fock radial wave functions (also by Towner and Hardy [4]) they yield a smaller correction of $\delta_{C2}(^{18}\text{Ne}) = 0.205(55)\%$. These two models thus disagree in the calculation of δ_{C2} at the level of 0.20(6)%, or 3.3σ, the largest such discrepancy for any of the 20 superallowed $0^+ \to 0^+$ Fermi β transitions with ft values experimentally measured to better than 3%. For ^{18}Ne, just like for ^{30}S and ^{42}Ti, there is a strong shell-closure effect that different models appear to be very sensitive to. In the most recent calculation performed by Satula *et al.* [14], the predicted isospin symmetry breaking correction is significantly larger than in any previous set of calculations. These calculations demonstrate a dramatic shell-closure effect that is also predicted for ^{30}S, which can be clearly seen in Figure 2. Differences between these state of the art calculations prompt a high-precision ft value determination for the ^{18}Ne superallowed decay, which would provide a particularly stringent test to discriminate between these theoretical models.

As part of a program to study the $T_Z = -1$ superallowed emitters, our goal is to improve the branching ratio for ^{18}Ne, which will help constrain the theoretical isospin symmetry breaking correction. This branching ratio has only been measured twice, once

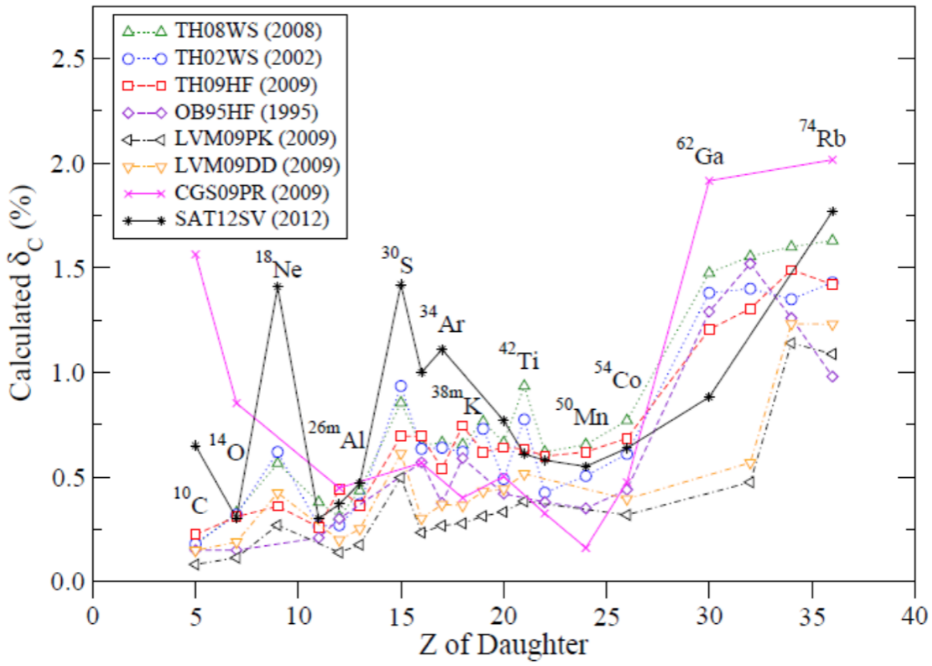

Figure 2: The δ_C isospin symmetry breaking correction as calculated by various models. ^{18}Ne is one of several (including ^{30}S and ^{42}Ti, all of which are $T_Z = -1$ emitters) superallowed decays for which there is a systematic increase in predicted δ_C value compared to its neighbours. The plot is based on Fig. 1 from Ref. [15].

in 1975 to be 7.70(21)% [16] with a precision of ±2.7% and once in 2015 to be 7.29(5)% [17] with a precision of ±0.7%, both of which can certainly be significantly improved by combining the available yields for ^{18}Ne at ISOLDE with the CENBG HPGe detector that has been calibrated in efficiency to a high precision.

Previously, the GANIL PAC accepted a proposal for experiment E622S, which proposed to measure the same quantity (the ^{18}Ne superallowed branching ratio) to similar precision. The experiment was performed in 2012 and the results were published in the thesis of Haïfa Bouzomita-Zran [17]. The ^{18}Ne branching ratio that was obtained, 7.29(5)%, was in good agreement with and a factor of 4 times more precise than the previous measurement, 7.70(21)%, of Ref. [16]. Unfortunately, the overall precision (±0.7%) was entirely limited by statistics and is not yet precise enough to discriminate between the theoretical predictions of isospin symmetry breaking. The present proposal is to improve this measurement by a factor of ∼ 2 in order to achieve the ±0.3% precision that is required.

2 Experimental Details

The ^{18}Ne branching ratio must be measured by directly detecting both the β particles and γ-rays emitted from the decays of ^{18}Ne. This will be done by implanting the ^{18}Ne ions into a tape-transport system with a plastic scintillator located at zero degrees relative to the beam axis, as shown schematically in Fig. 3. This detector setup has most recently been used at Jyväskylä in 2013 for half-life and branching ratios of ^{23}Mg and ^{27}Si [18], and is readily available for use in this experiment. Once sufficient activity is collected on the tape, the sample will be moved to the other side of the scintillator where a precisely calibrated germanium detector will be located 15 cm away. The 3 mm thick plastic scintillator, with a geometric efficiency of approximately 40%, will be used to trigger on β particles while the γ-rays will be detected by the HPGe detector with an efficiency calibrated to approximately $\pm 0.15\%$. The HPGe detector has been studied extensively, and the efficiency for detecting a 1042 keV γ-ray, as emitted by the IAS, is 0.2301(3)% [19].

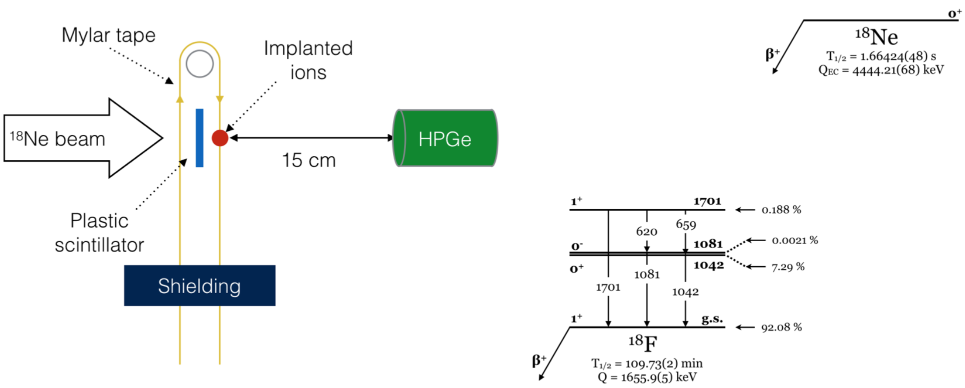

Figure 3: (Left) A schematic representation of the detection setup. Samples are implanted on the tape transport system, where a plastic scintillator (blue) is used to monitor the beam rate. The sample is then moved and both the plastic scintillator and the CENBG HPGe detector (green), placed precisely 15 cm from the sample, will be used to make the branching ratio measurement. The daughter activity will be removed behind lead shielding at the end of each cycle. (Right) The decay scheme for ^{18}Ne. The IAS is the 0^{+} excited state at 1042 keV, with a branch of approximately 7.3%.

The branching ratio is obtained by comparing the total number of β singles counts to the number of β-γ coincidences. Thus, the system will be triggered on β-γ events (collecting data in an event-by-event list mode), while the plastic scintillator will be simultaneously run in a scalar counting mode to record the total number of ^{18}Ne decay events. Although the plastic scintillator has a very small intrinsic dead time for processing events in scalar mode, we will limit the sample activity to 20 kHz. As learned from the experiment performed in 2012 at GANIL, this is to reduce the possibility of any rate-dependent corrections that would be difficult to estimate at the required level of precision.

Additionally, when one intends to trap samples of neon, a noble gas, in an aluminized Mylar tape transport system, the question of losses associated with diffusion must be addressed. We have performed GEANT4 simulations of the experiment to see what role even small amounts of diffusion would have on the measurement. It was found that because the branching ratio is obtained from a ratio of γ-counts to β-counts, diffusion effects essentially cancel. At the desired level of precision of 0.3% for the branching ratio, these effects can be safely ignored. Nonetheless, half-life measurements can be used as a method for estimating the rate of diffusion of a sample in the tape transport system. A loss of some implanted ions due to diffusion would result in a half-life measurement biased towards a smaller (shorter) value. Along the same vein, radioactive isotopes with longer half-lives are more sensitive to setting these limits.

3 Beam Time Request

Previous yield measurements for ^{18}Ne at ISOLDE span from 10^4 to several 10^6 ions/s using various target/ion source combinations. The proposed experiment can be achieved with rates from 1×10^5 to a few 10^6 ^{18}Ne/s by modifying the implantation time. For the sake of calculations, a rate of 1×10^5 ^{18}Ne is assumed. Additionally, the primary radioactive contaminant delivered with a ^{18}Ne beam is ^{18}F. Being the daughter of ^{18}Ne, it is unavoidable that some ^{18}F will be delivered and detected in the setup. However, in order to reduce the long-lived activity associated with its decay ($T_{1/2} = 110$ min), an upper limit of 10^4 ^{18}F/s delivered as a contaminant would be ideal.

Data will be collected in a cycles mode that will consist of: *i)* a 3 s measurement before the beam is turned on to determine the background level; *ii)* a 2 s collection period (beam on); *iii)* a 0.5 s period to move the tape to the decay counting position; and *iv)* a measurement time where the decays are counted for approximately 5 s before the entire cycle is repeated. The beam-on time of 2 s will be adjusted according to the beam intensity to ensure that the maximum counting rate of the plastic scintillator does not exceed 20 kHz. With these cycling times, a single cycle takes 10.5 s, and so approximately 340 cycles are collected every hour.

Using the above cycling times and assuming a nominal beam intensity of 1×10^5 ions/s the number of ^{18}Ne ions implanted in the tape at the start of the decay counting period is 1.1×10^5 ions. By counting the decays for 5 s (approximately 3 half-lives) 87.5% of the implanted ^{18}Ne will decay during this time. Using the β-decay branching ratio of 7.3% to populate the 1.042 MeV 0^+ state in the ^{18}F daughter, a γ-ray photopeak efficiency of 0.23% for the 1.042 MeV transition of interest, and with the known β efficiency of 40% the count-rate estimate for the number of 1.042 MeV γ-ray photopeaks is thus:

1.1×10^5 ions/cycle $\times$ 87.5% (^{18}Ne decays during 5 s) $\times$ 40% (β efficiency) $\times$ 0.23% (γ efficiency) $\times$ 7.3% (BR) $\times$ 340 cycles/h $\times$ 20 h/day = 44 000 β-γ events/day

In order to achieve the desired precision of 0.3%, we must measure a total of 160 000 β-γ events, requiring 3.6 days (11 shifts). This would result in a statistical precision of 0.25%, and when added in quadrature with the precision for the calibration of the HPGe detector of 0.15%, we arrive at our desired 0.3% precision for the superallowed branching ratio of ^{18}Ne.

As an additional measure of safety, we would also like to measure the rate of diffusion of our Ne sample out of the tape transport system. Although GEANT4 simulations indicate that at our desired precision for the branching ratio of ^{18}Ne the effects of diffusion are negligible, it would be beneficial to set a limit on the rate of diffusion observed with this tape. These measurements would prove to be useful not only for this experiment, but also for any future measurements performed at using this tape system that would be sensitive to effects from diffusion. To make this measurement, we propose to measure the half-lives of both ^{18}Ne and ^{19}Ne.

The half-life of ^{18}Ne can be performed by increasing the decay measurement time to 30 s for the cycle used for the branching ratio. In this case, we can achieve a statistical precision of 0.02% in 0.5 shifts:

1.1×10^5 ions/cycle $\times$ 40% (β efficiency) $\times$ 100 cycles/h $\times$ 4 h = 18 000 000 decay events

The longer-lived ^{19}Ne isotope would be much more sensitive to losses by diffusion on a larger time scale, as the half-life ($T_{1/2}$ =17.22 s) is an order of magnitude longer than ^{18}Ne. The ^{19}Ne yield has been measured at ISOLDE to be more than one order of magnitude more intense with the same target and ion source combination, at least 10^6 pps, therefore a half-life experiment achieving a statistical precision of 0.02% can also be performed in 4 hours. In this case, a cycle time of 3 s background, 1.2 s implant, 0.5 s tape move, and 350 s decay time would be used to measure the half-life. This cycle time limits the initial count rate to 20 kHz, and each cycle would consist of approximately 10^6 ^{19}Ne decays. We have:

1.1×10^6 ions/cycle $\times$ 40% (β efficiency) $\times$ 10 cycles/h $\times$ 4 h = 18 000 000 decay events

Summary of requested protons:
The total beam time request of 14 shifts consists of:

- 2 shifts for beam tuning and optimization
- 11 shifts for the superallowed branching ratio measurement of ^{18}Ne
- 0.5 shifts for a half-life measurement of ^{18}Ne
- 0.5 shifts for a half-life measurement of ^{19}Ne

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises:

one HPGe detector and one plastic scintillator + PMT with a tape transport system at LA1

Part of the Choose an item.	Availability	Design and manufacturing
[if relevant, name fixed ISOLDE installation: COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH]	☒ Existing	☒ To be used without any modification
HPGe detector ***Plastic scintillator + PMT*** ***Tape transport system***	☒ Existing	☒ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing

HAZARDS GENERATED BY THE EXPERIMENT

Additional hazards:

Hazards	*[Part 1 of the experiment/equipment]*	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure	**10^{-5} mbar**		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	**LN2 for HPGe, 10 L**		
Electrical and electromagnetic			
Electricity	**HPGe: 4500 V, PMT: 1000 V**		
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	**Aluminized Mylar tape**		
Beam particle type (e, p, ions, etc)	**18Ne, 19Ne**		
Beam intensity	**Up to 10^{7}**		
Beam energy	**30 keV**		
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☒ [ISO standard]		

• Isotope	**Co60, Cs137, Ba133, Eu152**		
• Activity	**A few kBq (standard ISOLDE sources)**		
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chemical agent], [quantity]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chemical agent], [quantity]		
Corrosive	[chemical agent], [quantity]		
Irritant	[chemical agent], [quantity]		
Flammable	[chemical agent], [quantity]		
Oxidizing	[chemical agent], [quantity]		
Explosiveness	[chemical agent], [quantity]		
Asphyxiant	[chemical agent], [quantity]		
Dangerous for the environment	[chemical agent], [quantity]		
Mechanical			
Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

0.1 Hazard identification

3.2 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, 220 V