EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

High-precision measurement of the ^{18}Ne superallowed β-decay *Q-value*

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Abstract

We propose to perform a high-precision measurement of the ^{18}Ne superallowed β-decay Q_{EC}-value using the Penning-trap mass spectrometer ISOLTRAP. The result will be used in the determination of the ^{18}Ne corrected $\mathcal{F}t$-value. Despite showing the biggest deviation to the world average the ^{18}Ne corrected $\mathcal{F}t$-value is among the least precisely known. We propose to measure the Q-value of the ground-state transition to a precision of 20 eV. The contribution of the Q_{EC}-value uncertainty to the uncertainty in $\mathcal{F}t$-value would then be pushed below the contribution of the half-life, which was recently measured at TRIUMF. Thus, the precision and accuracy of the $\mathcal{F}t$-value would be entirely limited by the contribution from the branching ratio measurement, and the Q_{EC}-value, so far a combination of a Penning-trap mass and one resulting from reaction measurements, would be set on solid ground. These data provide a test of the conserved vector current hypothesis and of the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix.

Requested shifts: 8

1. General Motivation

Superallowed Fermi β-decays occur between nuclear analog states with spin $J^{\pi} = 0^{+}$ and isospin $T = 1$, and depend uniquely on the vector part of the weak interaction. Precise experimental determinations of *ft*-values for these β-decays, along with small, theoretically calculated corrections, can provide a test of the conserved vector current (CVC) hypothesis, set limits on the existence of possible scalar currents, and contribute to the most demanding available test of the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. The *ft*-value is calculated from three experimentally determined quantities: the decay transition energy, Q_{EC}; the half-life of the parent state, $t_{1/2}$; and the branching ratio of the transition of interest, R. The *ft*-value is usually combined with theoretical corrections to yield a "corrected" $\mathcal{F}t$-value [1]:

$$\mathcal{F}t = ft\left(1+\delta_R'\right)\left(1+\delta_{NS}-\delta_C\right) = \frac{K}{2G_V^2(1+\Delta_R^V)}. \quad (1)$$

The terms that modify *ft* are δ_R' and δ_{NS}, which comprise the transition dependent part of the radiative correction, and δ_C, the isospin-symmetry-breaking correction. The term Δ_R^V is the transition independent part of the radiative correction, K is a constant, $K/(\hbar c)^6 = 8120.2776(9) \times 10^{-10}$ GeV^{-4}·s, and G_V is the vector coupling constant. According to the CVC hypothesis, G_V, and hence $\mathcal{F}t$, should be the same for all superallowed β-decays.

In the most recent critical survey of all experimental and theoretical superallowed β-decay data [1], 14 transitions, with $\mathcal{F}t$-value uncertainties of less than ±0.4%, were used to determine the world-average $\overline{\mathcal{F}t}$-value. Entering to the fifth power in the calculation of the $\mathcal{F}t$-value, precise and accurate Q_{EC}-values are extremely important for the determination of $\mathcal{F}t$. Over the last decades, Penning traps have proven themselves as the tool of choice for performing such measurements. The improved precision and accuracy they have provided compared to nuclear reaction data revealed that in some cases previously accepted values [2] were incorrect by as much as 6σ [3–5]. Following the recent determination of the Q_{EC}-value for ^{14}O [6] with the LEBIT Penning-trap at the NSCL, all 14 of the high-precision superallowed transitions have now Q_{EC}-values determined with a Penning trap.

In the 2015 survey of Ref. [1], 4 additional transitions (in ^{18}Ne, ^{26}Si, ^{30}S, and ^{42}Ti) with complete experimental data sets—measured values for Q_{EC}, $t_{1/2}$ and R—were evaluated, but were not precise enough to be included in the mean $\mathcal{F}t$-value calculation ($\overline{\mathcal{F}t}$). Since then, the

experimental data has been improved for ^{42}Ti, and obtained for ^{46}Cr, ^{50}Fe, and ^{54}Ni for the first time [7,8]. Nonetheless, the precision reached for the latter transitions is not yet high enough to contribute to $\overline{\mathcal{F}t}$. Hence, there are now 21 transitions with complete data sets. Of the 7 less precise $\mathcal{F}t$-values, ^{18}Ne shows the largest deviation from $\overline{\mathcal{F}t}$ (see Figure 1). The uncertainty in $\mathcal{F}t$ for ^{18}Ne is dominated by the 2.7% fractional uncertainty in the branching ratio, from a single measurement made in 1975 [9]. A new but unpublished measurement was recently performed at SPIRAL, GANIL with a 0.7% fractional uncertainty [10] with further improvement being in reach at ISOLDE/CERN [11]. In addition, the ^{18}Ne half-life was recently measured to be $t_{1/2}$ = $1.66400^{+0.00057}_{-0.00048}$ s [12], approximately two times more precise than the previously accepted value [13]. Therefore, an improved determination of the ^{18}Ne Q_{EC}-value of the superallowed transition to the daughter 0^+ state in ^{18}F is required with the aim to push the uncertainty to the same level as the most precise theoretical correction. The ground-state transition Q-value is obtained from a Penning-trap measurement at ISOLTRAP for ^{18}Ne (see inset of Fig. 2) [14] and nuclear reaction data for the daughter, ^{18}F [15,16]. The uncertainty on the ground-state transition Q-value is currently 589 eV [17] whereas the excitation energy of the daughter 0^+ state is known to a precision of 80 eV [1]. Hence, more than a factor 3.5-fold improvement on the ground-state Q-value is needed to bring down the contribution to the ^{18}Ne $\mathcal{F}t$-value uncertainty due to the superallowed Q_{EC}–value to at least the same level as that due to $t_{1/2}$. Additionally, the data from the two reactions determining the AME mass of ^{18}F [15,16] both deviate from the adjusted AME input by more than 1.5 standard deviations [17]. In order to avoid systematic errors on the Q_{EC}-value it would be necessary to use the Penning-trap technique, which has been time and time again proven to yield not only precise but also accurate results.

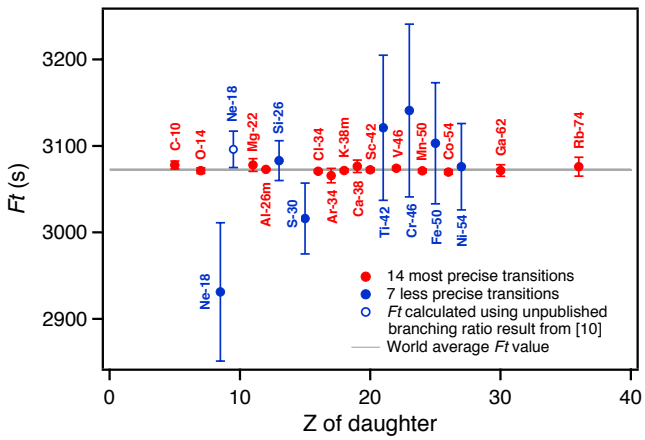

Figure 1: $\mathcal{F}t$-values vs. Z of the daughter nucleus for the 14 most precisely determined transitions (in red) used to

determine the world average $\mathcal{F}t$-value, and for 7 less precisely determined transitions (in blue). The open blue circle shows the ^{18}Ne $\mathcal{F}t$-value calculated using the unpublished branching ratio measurement of Ref. [10].

2. Experimental techniques

The proposed measurement of the ^{18}Ne superallowed β-decay Q_{EC}-value will be performed using the ISOLTRAP [18] apparatus at ISOLDE/CERN. The current ISOLTRAP setup combines three different ion trapping techniques for ion beam cooling, bunching and purification for high-precision mass measurement. With this sequence of beam preparation stages, it has been possible to perform high-precision mass measurements even with contaminants three or four orders of magnitude more abundant than the ion of interest.

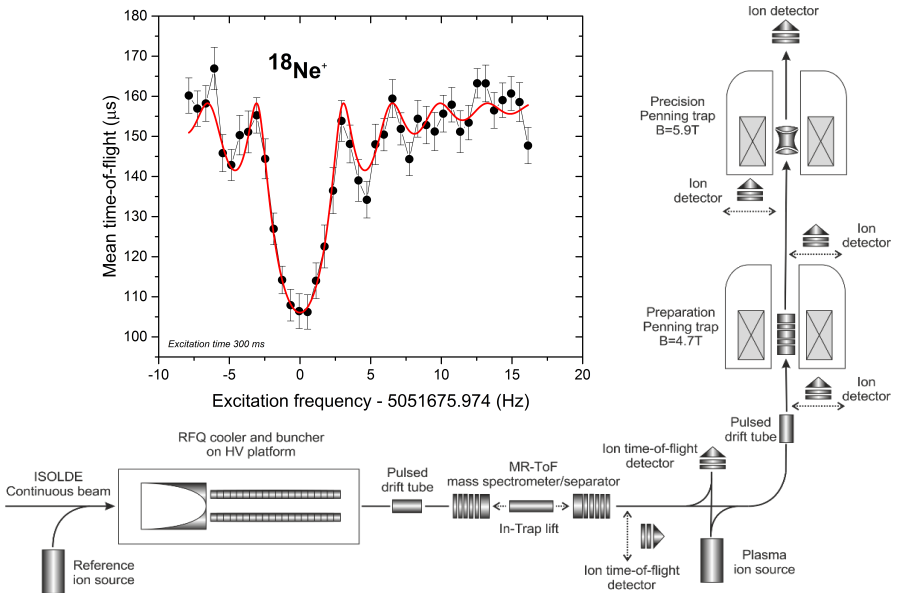

Figure 2: Schematic overview of the current ISOLTRAP setup. Inset: Example of a $^{18}Ne^{+}$ ToF-ICR resonance obtained at ISOLTRAP for an excitation time of 300 ms [14].

A schematic view of the ISOLTRAP mass spectrometer is presented in Figure 2. The Q_{EC}-value determination will be performed using the precision Penning trap and the well-established Ramsey-type time-of-flight ion-cyclotron-resonance (ToF-ICR) technique [19], or the recently implemented Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) technique [20].

The Q_{EC}-value is defined as the energy equivalent of the mass difference between parent and daughter atoms

$$Q_{EC} = \left(M_p - M_d\right)c^2 = \left(\frac{f_c^d}{f_c^p} - 1\right)\left(M_d - M_e\right)c^2 = (R-1)\left(M_d - M_e\right)c^2, \quad (2)$$

where the indices p and d refer to the parent and daughter respectively, R is the ratio of the cyclotron frequencies between daughter and parent and M_e is the electron mass. The aim of the proposed experiment is to measure the ground-state transition Q_{EC}-value of the isobaric pair ^{18}Ne/^{18}F to a precision of about 20 eV thus improving the current uncertainty by a factor 30. Hence, the contribution of the ground-state masses in the uncertainty of the superallowed Q_{EC}-value would become significantly smaller than the contribution from the uncertainty in the excitation energy of the daughter 0^+ state in ^{18}F. Very recently, the mass differences of the pairs ^{21}Na/^{21}Ne and ^{23}Mg/^{23}Na were determined by ISOLTRAP using the Ramsey type ToF-ICR technique to a precision better than 20 eV and 30 eV respectively, thus demonstrating the spectrometer's ability to determine Q-values with a relative precision of a few 10^{-6} [21]. In the present case, to reach an uncertainty on the Q_{EC}-value on the order of 20 eV the cyclotron frequency ratio between daughter and mother nuclides has to be determined to a relative precision of about 10^{-9}. The statistical uncertainty in f_c obtained using the single excitation-pulse ToF-ICR technique is approximately given by

$$\frac{\delta f_c}{f_c} = \frac{1}{f_c T_{rf} \sqrt{N}}, \quad (3)$$

where T_{rf} is the measurement time for the ion inside the trap and N is the total number of ions collected during a measurement of the cyclotron frequency. Hence, for $T_{rf} = 600$ ms and N~1000, the frequency of each species of interest could be determined in a single measurement to a relative precision of 10^{-8} yielding a statistical uncertainty of 250 eV on the value of the ground-state Q_{EC}-value. With a Ramsey-type excitation scheme [19] one can gain a factor 3 in precision. Hence, the desired precision can be reached in about 20 measurements of R.

In order to reduce the systematic errors to a minimum and to achieve the target precision, it is necessary to measure the cyclotron frequencies of the parent and daughter isobars in the same run, meaning in the same experimental conditions. Furthermore, to determine the Q_{EC}-value with a precision of 20 eV, the beam sent to ISOLTRAP's measurement Penning trap should be purely composed of the species under study. Table 1 presents the mass resolving power required to separate ^{18}Ne from ^{18}F as well as from the two most probable stable contaminants we should be facing, namely ^{18}O and H_2O. The MR-ToF isobar separator, which can routinely achieve a mass resolving power on the order of 10^5, is in itself by far sufficient to separate the pair of interest

and the stable contamination. Finally, to minimize charge-exchange losses in the ISOLTRAP buncher, the buffer-gas inlet will be cooled with liquid nitrogen and the bunching time will be optimized [14] which requires additional time for optimization. We note that studying the trapping, cooling and bunching of positive fluorine ions within an RFQ cooler and buncher is also of high interest for the INTC-I-171 LOI [22].

3. Beam time request

Element	Half-life	Mass Excess [keV]	unc. [keV]	Mass resolving power to ^{18}Ne	Yield [ions/ μC]
^{18}Ne	1.6 s	5317.6	0.4	-	2.10^5
^{18}F	109.7 min	873.1	0.5	3 800	1.10^6
^{18}O	stable	-782.8156	0.0007	2 800	stable
H_2O	stable	9840.9398	0.0002	3 700	stable

Table 1: Half-life, Mass Excess [17] and Mass resolving power for ^{18}Ne and ^{18}F as well as the stable contaminant ^{18}O and H_2O. The expected yields for ^{18}Ne and ^{18}F using SiC/VD5 unit are also presented [23].

We propose to use a SiC target coupled to a VADIS hot transfer line ion source (VD5) to ease the effusion of atomic F towards the ionisation region. The yield of ^{18}F was measured to be $1.8x10^7$ ions/μC at the ISOLDE-SC. More recent measurements of $^{27}Al^{18}F^+$ with an intensity of $1.7x10^7$ ions/μC were reported from the offline separator. Assuming a factor 10 loss with respect to the molecular sideband, one would thus expect a yield of $1x10^6$ ions/μC of atomic ^{18}F [23]. For ^{18}Ne, ISOLDE-SC yields are reported using a SiC-MK5 target/ion source combination. The enhancement factor brought by the use of the more recent VD5 ion source over the MK5 plasma ion source would put the expected yield of ^{18}Ne at the level of about $2x10^5$ ions/μC [23]. Hence, it seems feasible to extract both species from the same target and ion source unit. We note that neon masses down to ^{17}Ne have already been measured with ISOLTRAP [24].

If the measurement is performed with an average of one ion per measurement cycle in the trap (to minimize possible frequency shifts due to the Coulomb interaction), and assuming a total cycle time of 1 s, then a resonance could be obtained in less than 50 mins. In order to obtain a fully uncorrelated data set, each measurement of the frequency ratio *R* necessitates the measurement of three ToF-ICR resonances (^{18}F-^{18}Ne-^{18}F). Hence, 50 hours or equivalently 6

shifts are necessary to reach the aimed uncertainty of 20 eV. Additionally, 1 shift is required to tune the transport from ISOLDE into ISOLTRAP, study the charge exchange phenomenon, and optimise the transport towards the precision Penning trap. Finally, we request one additional shift to verify the robustness of the result to systematic detuning of the setup. For systematic cross-checks a few PI-ICR resonances will also be taken.

Summary of requested shifts : We request 6 shifts for measurements, 1 shift for tuning and 1 shift for systematic investigations.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: ISOLDE central beam line and ISOLTRAP setup. The ISOLTRAP setup has safety clearance, the memorandum document 1242456 ver.1 “Safety clearance for the operation of the ISOLTRAP experiment” by HSE Unit is released and can be found via the following link: https://edms.cern.ch/document/1242456/1.

Part of the	Availability	Design and manufacturing
ISOLTRAP setup	☒ Existing	☒ To be used without modification

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed ISOLTRAP installation.