TRIUMF - EEC SUBMISSION EEC meeting: 201307S *Original Proposal*	TRIUMF	**Exp. No.** S1445 - *Approved* **Date Submitted:** 2013-06-12 11:36:15

Title of Experiment:

High precision mass measurements for the determination of ^{74}Rb's Q-value

Name of group:

TITAN

Spokesperson(s) for Group

S. Ettenauer, T. D. Macdonald

Safety Coordinator(s) for Group

Current Members of Group:
(name, institution, status)

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Beam Shift Requests:

10 shifts on: ISAC

2 shifts on: OLIS

Comment:

(2 shifts requested as per the detailed statement)(updated March 12, 2014 as per instructions from the Science Division Head).

Basic Information:

Date submitted: 2013-06-12 11:36:15

Date experiment ready:

Summary:

The Q EC-value of 74Rb currently dominates the uncertainty of its ft-value, which is important for the extraction of the CKM matrix element V ud from superallowed 0 + → 0 + nuclear β-decays. 74Rb has the largest isospin-symmetry breaking corrections δ C of all 13 superallowed decays considered in the evaluation of V ud. It would hence carry particular weight to discriminate between conflicting theoretical models of δ C if 74Rb's Q EC-value was known more precisely. Thus, we propose new direct mass measurements of 74Rb and 74Kr at the TITAN mass spectrometer. We intend to employ highly charged ions with charge states up to q = 27+, which will determine the Q EC-value with an uncertainty of 700 eV or below.

Plain-text summary:

Primary Beamline: isac2a

ISAC Facilities

ISAC Facility: TITAN Yield

ISAC-I Facility:

ISAC-II Facility:

Secondary Beam

Isotope: Rb-74, Kr74

Energy: 20

Intensity Requested: 10 000

Minimum Intensity: 3 000

Maximum Intensity: 10^7

Energy Units: keV

Energy spread-maximum:

Time spread-maximum:

Angular Divergence:

Spot Size:

Charge Constraints:

Beam Purity:

Special Characteristics:

Beam Delivery Information

Target Material(s): ZrC Nb

Ion Source: SIS/RILIS

Comments:

Beam Readiness Review Comments:

Facility: TITAN

Requested Isotopes /Energy /Minimum Intensity: 74Rb, 74Kr / 20 keV / 3e3 pps

Established yields: 74Rb: > 1e4 pps; 74Kr: 8e5 pps

Comments: Minimum beam intensity is no problem. Shifts can be approved.

Experiment Support

Beam Diagnostics Required:

Signals for Beam Tuning:

DAQ Support:

TRIUMF Support:

All equipment is in place and running. Only normal operating support from TRIUMF is required.

NSERC:

Other Funding:

Muon justification:

Safety Issues:

Safety issues for the TITAN experiment have been already addressed in the required documents and have met approval. A safety request for the specific beams of this proposal will be made after the decision of the EEC.

(a) Scientific value of the experiment

The unitarity test of the first row in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix, $|V_{\mathrm{ud}}|^2 + |V_{\mathrm{us}}|^2 + |V_{\mathrm{ub}}|^2 = 1$, poses stringent limits on physics beyond the Standard Model (SM) of particle physics [52]. Recently, novel lattice QCD-calculations of involved form factors reduced the uncertainty contribution of $|V_{\mathrm{us}}|$ to this test [9]. Consequently, $|V_{\mathrm{ud}}|$ now dominats its overall uncertainty.

Studies of superallowed $0^+ \to 0^+$ nuclear β-decays [21] with their ever increasing precision remain the preferred way to access V_{ud} despite complementary neutron β-decay measurements, which do not suffer from nuclear structure complications. The challenges of the nuclear many-body problem would inevitably compromise any study at the precision frontier were it not due to the specific nature of superallowed $0^+ \to 0^+$ nuclear β-decays. First, since initial and final nuclear spin are $I_i = I_f = 0$, the decay is a pure Fermi transition (at least at the tree-level). Following the conserved vector current hypothesis (CVC), this implies that in contrast to Gamow-Teller transitions its coupling constant is not renormalized in the nuclear medium. Secondly, a superallowed decay proceeds between isobaric analog states in parent and daughter nuclides which reduces the calculation of the nuclear matrix element M_0 to a simple isospin raising operation. Hence, nuclear structure effects are small (on the order of ~ 1 %) and only enter through nuclear structure dependent radiative corrections, δ_{NS} (higher order loop effect), and more significantly through isospin-symmetry breaking corrections δ_C. These take into account that isospin does not reflect an exact symmetry of the SM as evident by the difference in mass and electric charge between proton and neutron. Hence, in addition to their distinction in isospin projection T_z, isobaric analog states slightly differ in their nuclear wave-functions and the nuclear matrix element is modified to $\mid M \mid^2 = \mid M_0 \mid^2 (1 - \delta_C)$.

Together with transition dependent radiative corrections, δ'_R, the experimental ft-value characterizing a nuclear β-decay is for superallowed $0^+ \to 0^+$ transitions corrected to

$$\mathcal{F}t = ft(1 + \delta'_R)(1 + \delta_{NS} - \delta_C), \tag{1}$$

which, according to the CVC hypothesis, is the same for all superallowed cases with the same isospin T. For $T = 1$, the corrected $\mathcal{F}t$-value relates to V_{ud} following

$$\mathcal{F}t = \frac{K}{2G_F^2 \mid V_{\mathrm{ud}} \mid^2 (1 + \Delta_R^V)}, \tag{2}$$

where K is a numerical constant, G_F is the Fermi constant, and Δ_R^V is a transition independent radiative correction. To date, 13 nuclei contribute to the averaged $\overline{\mathcal{F}t}$-value and to the extraction of V_{ud} through superallowed β-decays. In each case the ft-value depending on half-life, branching ratio (BR), and transition energy (or Q_{EC}-value) of the superallowed transition is measured to a relative precision of better than 0.4 % [21].

Within recent years, the isospin-symmetry breaking corrections δ_C have received a strong focus of research. In the past, a theoretical uncertainty was assigned to δ_C due to discrepancies between δ_C calculated in the nuclear shell model with Hartree-Fock radial wave-functions (SM-HF) by Ormand and Brown [36, 37, 38, 39] and in the shell model with Saxon-Woods radial wave-functions (SM-SW) by Towner and Hardy [49, 50]. In [21], Towner and Hardy have introduced their own SM-HF calculation which are due to an increased model space and a new calculation protocol in better agreement with their own SM-SW approach, hence reducing the associated systematic theoretical uncertainties. Currently, these two calculations of δ_C are considered in the survey of superallowed β-decays [21].

Nevertheless the remaining differences between SM-HF and SM-SW do not allow one to take full advantage of the achieved experimental precision. This was recently highlighted by a new precision

half-life measurement of ^{26m}Al performed at TRIUMF [16]; the experimentally improved ft-value for ^{26m}Al increased the discrepancy between the SM-SW and SM-HF derived $\overline{\mathcal{F}t}$-values. Novel approaches to the calculation of δ_C have recently been published in [1, 29, 30, 41, 42]. Some of them show large deviations to δ_C based on SM-HF and SM-SW, but they generally need further development. Finally, the approaches by Towner and Hardy have been criticized on formal grounds [34, 35].
In the debate on the isospin symmetry breaking corrections, experiment can provide guidance for theory along two lines. Firstly, some models rely on experimental quantities such as nucleon separation energies, charge radii, spectroscopic factors, coefficients of the IMME, or excitation energy of other 0^+ states as input for their calculations. Improved input values will strengthen the respective model. For instance, a recent TRIUMF measurement of the charge radius of ^{74}Rb [31] reduced the uncertainty in δ_C based on SM-SW, which was previously based on a charge radius extrapolated from stable isotopes. Conversely, an observable which is not needed to fine-tune a model, could serve as an independent benchmark of the model, as done for example in a comparison of measured and theoretical transition strength to non-analog 0^+ states [23].
Secondly, experiment can contribute to the theoretical discussion regarding δ_C by more precise ft-values, either of the 13 most studied cases or of new ones. These measurements can highlight discrepancies between a set of δ_C, the CVC hypothesis, and experimental results. Particularly, superallowed β-emitters with large δ_C offer the opportunity to discriminate between different models. Although the recently studied superallowed decay branch in ^{32}Cl proceeds via isobaric analogue 1^+ states, it is almost entirely a Fermi transition with only negligible Gamow-Teller contributions [33]. With $\delta_C \approx 5\%$, it is found to have a much larger isospin symmetry breaking correction than any of the 13 precision $0^+ \rightarrow 0^+$ cases. Lending strong support to the theoretical model, ^{32}Cl's $\delta_C = 4.6(5)\%$ obtained from SM-SW agrees well with an 'experimental' $\delta_C^{\mathrm{exp}} = 5.3(9)\%$ [33] (see also Figure 1a). The latter is extracted assuming CVC and is based on an improved measurement of ^{32}Cl's BR and hence its ft-value, its uncontroversial theoretical corrections δ'_R and δ_{NS}, as well as the averaged $\overline{\mathcal{F}t}$-value of the 13 $0^+ \rightarrow 0^+$ cases.
In the framework of the shell model the isospin symmetry breaking corrections $\delta_C = \delta_{C1} + \delta_{C2}$ are separated into configuration mixing within the restricted shell model space, δ_{C1}, and the radial overlap correction, δ_{C2}. In ^{32}Cl, δ_C is large because of a dominating contribution of configuration mixing, $\delta_{C1} = 3.75(45)\%$. In comparison, the largest δ_{C1} of the 13 well-studied $0^+ \rightarrow 0^+$ decays is found in ^{62}Ga with $\delta_{C1} = 0.350(40)\%$ [50]. Given that the uncertainty of δ_C^{exp} in ^{32}Cl is larger than the radial overlap correction $\delta_{C2} = 0.85(3)\%$, this benchmark is more sensitive to δ_{C1} than it is to δ_{C2}. The reported uncertainties would still allow good agreement between δ_C and δ_C^{exp} for one out of three considered interaction Hamiltonians even if δ_{C2} was in fact a factor of 4 smaller (Figure 1b). For $0^+ \rightarrow 0^+$ decays, δ_C is consistently dominated by the radial overlap correction δ_{C2}, e.g. in ^{62}Ga $\delta_{C2} = 1.25(25)\%$ (see Figure 1a). Most new models result in smaller δ_C and in Ref. [35] a reduction of δ_{C2} is expected because of neglected radial excitations in the shell model approaches by Towner and Hardy. Consequently, the isospin symmetry breaking corrections currently considered in the survey of superallowed β-decays would also benefit from benchmarks more sensitive to δ_{C2}.
^{74}Rb has the highest atomic number, Z, among the 13 precision superallowed β emitters. Due to the approximate $\delta_C \sim Z^2$ scaling [1], it has the largest isospin symmetry breaking corrections of those 13 cases. Consequently, ^{74}Rb would serve best to discriminate between models if the precision of its experimental ft-value were not limited by its Q_{EC}-value. For instance in the proposed comparative benchmarks of models for δ_C [51] (but also in the extraction of V_{ud} by semi-empirical techniques [20]) ^{74}Rb would carry particular weight if its ft-value was known to a precision already achieved in a majority of the other cases (compare with Figure 2).
Since transition energies are equivalent to mass differences of parent and daughter states, the ex-

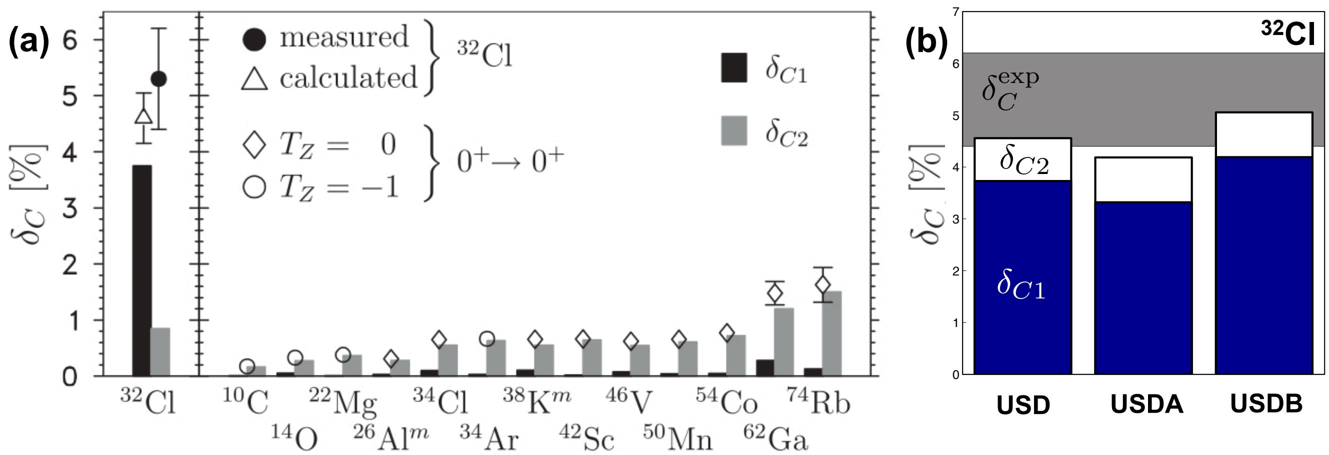

Figure 1: (a) Isospin symmetry breaking corrections δ_C in ^{32}Cl ('measured' and calculated with SM-SW) in comparison to δ_C of $0^+ \to 0^+$ decays (again SM-SW). $\delta_C = \delta_{C1} + \delta_{C2}$ are separated into configuration mixing within the restricted shell model space, δ_{C1}, and the radial overlap correction, δ_{C2}. (b) δ_C of ^{32}Cl calculated with different interaction Hamiltonians in comparison to δ_C^{exp}. While the uncertainty adopted for δ_{C1} in [33] represents half of the spread of the plotted results, the error in δ_{C2} additionally contains the range of results due to adjusting the strength of the Saxon-Woods potential and the uncertainty in the Saxon-Woods radius parameter [33]. Figure (a) from [33].

Table 1: Mass excess (m.e.) of ^{74}Rb and ^{74}Kr required to determine the Q_{EC}-value of ^{74}Rb from direct mass measurements.

Quantity	ISOLTRAP [keV]	TITAN [keV]	all data [keV]
m.e. (^{74}Rb)	-51 914.7(3.9) [26]	-51 916.5(6.0)[15]	-51 915.2(3.3)
m.e. (^{74}Kr)	-62 332.0(2.1) [40]		-62 332.0(2.1)
Q_{EC}-value			10 416.8(3.9)

traction of V_{ud} from superallowed β-decays has profited by the introduction of Penning trap mass spectrometry to the realm of rare isotope science (see Ref. [12] and references therein). To date, these spectrometers [3, 5] are unmatched in precision and accuracy for masses of nuclides with half-lives down to 10 ms [48]. During the last decade, deficiencies in previously adopted Q_{EC}-values of superallowed β-decays have been exposed and resolved by Penning traps [43, 10, 11, 12]. With the exception of ^{14}O, all Q_{EC}-values are now based on Penning trap mass measurements. For ^{74}Rb, these include three measurement campaigns at ISOLTRAP [22, 25, 26] and a measurement at TITAN (closed proposal S966) utilizing highly charged ions (HCI) for the first time in Penning trap mass spectrometry of radioactive nuclides [15]. Nevertheless, the Q_{EC}-value remains the dominating uncertainty of ^{74}Rb's ft-value (see Figure 3). The challenge for precision measurements is found in ^{74}Rb's short half-life ($t_{1/2} = 65$ ms) (see also Section (b) for a more detailed discussion). The measurements at ISOLTRAP (and Penning trap mass measurements of rare isotopes in general) were performed with singly charged ions, i.e. $q = 1+$. On the other hand, HCI present an opportunity to boost the measurement precision by increasing the charge state q prior to the measurement. Hence, although ISOLTRAP's combined mass uncertainty of 3 measurement campaigns is of comparable precision to the measurement at TITAN (see Table 1), the latter of which was achieved in less than 22 h of

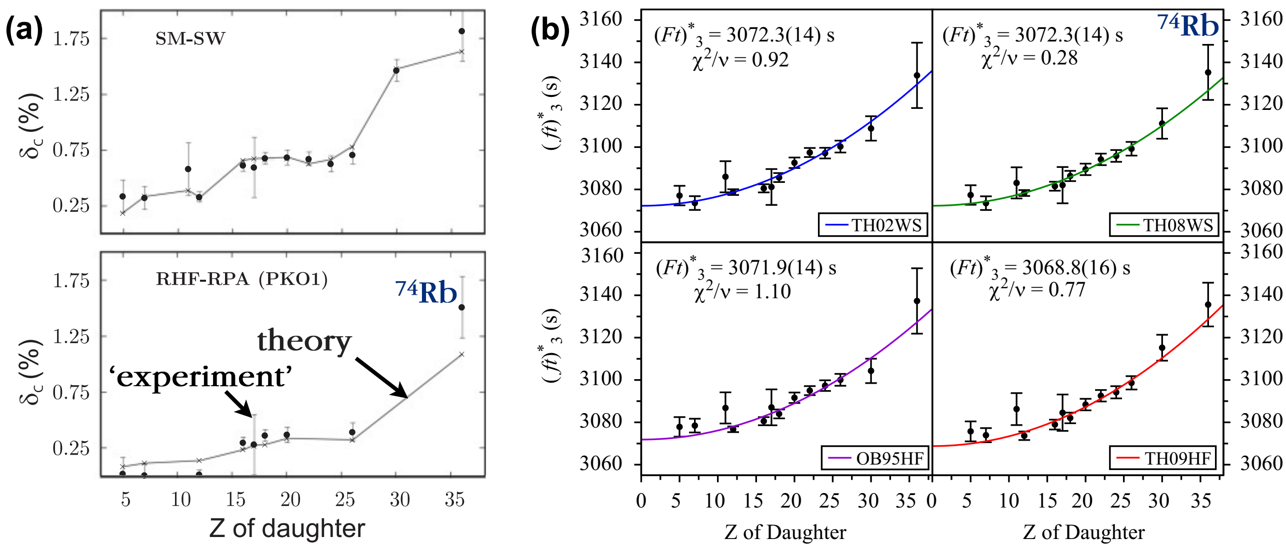

Figure 2: **(a) A comparative test between models of isospin symmetry breaking corrections** introduced by Towner and Hardy [51]. Following $\delta_C = 1 + \delta_{NS} - \overline{\mathcal{F}t}/[(1+\delta'_R)\cdot ft]$, $\overline{\mathcal{F}t}$ is treated as a single free parameter to minimize the difference in all available cases between δ_C and $1 + \delta_{NS} - \overline{\mathcal{F}t}/[(1+\delta'_R)\cdot ft]$. As a figure of merit the reduced χ^2 was employed. Figure from [51].
(b) A semi-empirical viewpoint [20] tries to emphasize similarities, and not differences, between different models of δ_C. Especially, the shell model calculations of δ_C show similar relative patterns in the development of δ_C over Z, though their absolute values might differ. Individual models are only considered for their representation of nuclear structure effects but not for their general (approximate) Z^2 behaviour. Instead of correcting all individual superallowed cases to the transition independent $\mathcal{F}t$-values, one only corrects by the shell-structure effects in δ_C and extrapolates the resultant $\widetilde{ft}$-values to the charge-independent limit where isospin-symmetry breaking and Coulomb effects are negligible. Figure from [20].
As apparent from the figures in (a) and (b), both approaches would be strengthened in their conclusions by a more precise ft-value and hence Q_{EC}-value for ^{74}Rb.

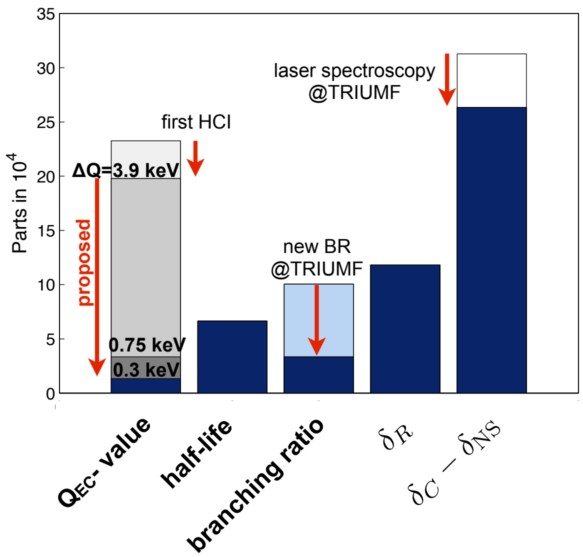

Figure 3: Partial uncertainties to ^{74}Rb's corrected $\mathcal{F}t$-value. The experimental ft-value based on Q_{EC}-value, half-life $t_{1/2}$, and branching ratio is corrected to the $\mathcal{F}t$-value considering radiative corrections δ'_R and the nuclear structure depended corrections $\delta_C - \delta_{NS}$. Measurements at TRIUMF have recently contributed to improvements in the Q_{EC}-value [15], the branching ratio [2], and the charge radius [31] which is an input parameter in the calculation of δ_C based on SM-SW.

beamtime by profiting of the precision advantage offered by HCI. A significant further reduction in the uncertainty of ^{74}Rb's Q_{EC}-value (in a reasonable measurement time) can only be envisioned by employing novel techniques such as HCI at TITAN. In fact, our first ^{74}Rb measurement suffered from a turbo pump failure during the online beamtime that necessitated the reconditioning and retuning of the TITAN facility and resulted in a lower system efficiency. Furthermore, due to the novelty of the technique at the time, the charge state of $q = 8+$ utilized in [15] was not as high as charge states attainable now (see Section (b)).

Hence, we propose a new comprehensive set of mass measurements including ^{74}Rb and its daughter ^{74}Kr with HCI in $q = 19 - 27+$ in order to obtain a Q_{EC}-value with an uncertainty of 700 eV or less. As a result, the contribution of the Q_{EC}-value to the uncertainty of ^{74}Rb's ft-value will be the smallest among all experimental inputs, including the recent branching ratio measurement at TRIUMF [2] (see Figure 3). Such a Q_{EC}-value measurement will reduce the uncertainty of the $\mathcal{F}t$-value by $\sim 25\%$. Perhaps most importantly, ^{74}Rb would with a precisely known Q_{EC}-value carry particular weight in comparisons of conflicting theoretical models of δ_C similar to [51] since it has the largest δ_C among all superallowed $0^+ \to 0^+$ β-emitters. This could challenge perceived consistencies between a set of δ_C calculations, experimental results, and the conserved vector current hypothesis.

(b) Description of the experiment

The proposed measurement is to be performed with TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN). The TITAN facility is currently an ensemble of three ion traps dedicated to, but not limited to, the preparation and manipulation of short-lived ions for high precision mass measurements [8]. These traps are a radio-frequency quadrupole (RFQ) linear Paul trap, an electron beam ion trap (EBIT), and the measurement Penning trap (MPET), all of which are depicted in Figure 4. The radioactive ion beam is received from ISAC by the TITAN-RFQ, where it is accumulated, cooled, and bunched [7]. The ion bunch is then extracted from the RFQ as singly charged ions (SCI) and either steered into the EBIT for an increase to their charge state [18, 28], or steered directly into the MPET for the mass measurement. For ^{74}Rb and ^{74}Kr, the RFQ, EBIT and MPET will all be required. Additionally, a cooler Penning trap (CPET) [24, 45, 47] and multi-reflection time-of-flight spectrometer (MR-TOF) [53] are being assembled and commissioned for the TITAN facility to provide a cooling mechanism for future mass measurements with highly charged ions (HCI) and isobarically clean beams. The possible use of these additional traps for the proposed experiment, and the additional time required for beam preparation, would need to be balanced with the short half-life of ^{74}Rb ($t_{1/2}$=65ms) .

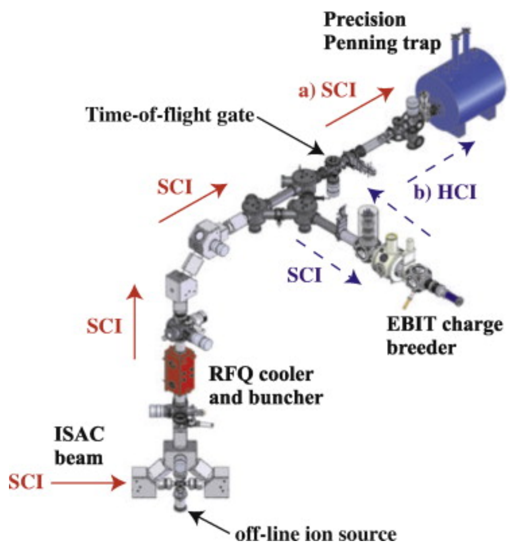

Figure 4: The TITAN beam line and ion trap configuration. Ions are sent from the RFQ to the MPET for mass measurements, but can first be sent to the EBIT charge breeder.

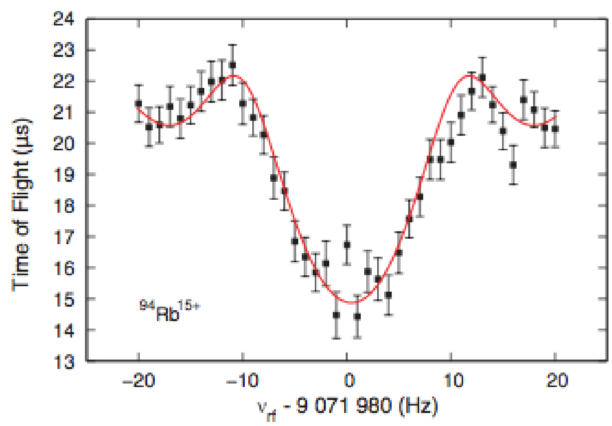

Figure 5: An example resonance [46] from applying the ICR-TOF technique of ^{94}Rb^{15+} for T_{RF} = 77 ms. The solid line is a fit of the theoretical line shape to the data.

Inside the MPET, the ion-cyclotron-resonance time-of-flight (ICR-TOF) technique [27] will be used to produce a TOF spectrum with a resonance occurring at the cyclotron frequency, ν_c. An example of such a spectrum can be seen in Figure 5. The cyclotron frequency is obtained by fitting the theoretical line shape to the data and it is related to the mass according to $\nu_c = \frac{1}{2\pi}\frac{q}{m}eB$. The attainable precision for a mass measurement using the ICR-TOF technique scales as

$$\frac{\delta m}{m} \propto \frac{m}{qe\ B\ T_{rf}\ \sqrt{N_{ions}}}, \tag{3}$$

where m is the mass of the ion, B is the magnetic field in the MPET, qe is the charge of the ion in charge state q, T_{rf} is the excitation time, and N_{ions} is the number of detected ions. An additional factor of 2-3 in precision can be gained over conventional ICR-TOF by employing a Ramsey excitation sheme [32, 19], which will be used in the proposed measurement of ^{74}Rb and ^{74}Kr.

To determine the magnetic field precisely at the time of measurement, calibration measurements are performed with an ion of well known mass. Based on the mass of this reference ion, m_2, the mass of the ion of interest, m_1, is deduced from the frequency ratio: $m_1 = \frac{q_1}{\nu_1}\frac{\nu_2}{q_2} \cdot m_2$. In order to limit the uncertainty contribution of the reference ion, an isotope of well known mass needs to be chosen. For both ^{74}Rb and ^{74}Kr, we request ^{74}Ge from OLIS, which has a relative mass uncertainty of 0.8 parts-per-billion (ppb). To reduce possible systematic effects in the Q_{EC}-value, ^{74}Kr would be measured under all the same conditions as ^{74}Rb, including excitation scheme, charge state, and use of reference ion thus minimizing any m/q dependent effects. Possible m/q dependent effects have been well investigated with SCI, and have relative uncertainties in the frequency ratio on the order of $\sim \Delta(m/q) \cdot 10^{-10}$ [6]. Analogous studies with HCI, documented in [13], did not reveal m/q dependent shifts either, although the precision of these investigations was lower than in [6]. Hence, additionaly detailed studies are underway to confirm the required accuracy as expected from work with SCI. A comprehensive discussion of other systematic uncertainties relevant for HCI can be found in [13].

Table 2: Summary of required beam, targets, ion sources, and yields

Isotope	$\delta m/m$	Required Yield	Target + Proton	Ion Source	ISAC Yields (2010)
^{74}Rb	3-7 ppb	3×10^3 ions/s	Nb + 98 mA	Surface	1.7×10^4 ions/s
^{74}Kr	3-7 ppb	3×10^3 ions/s	ZrC + 75 mA	FEBIAD	8.4×10^5 ions/s
^{74}Ge	reference	–	–	OLIS	–

For the production of ^{74}Rb we request a 100 μA proton beam on a Nb-target with a surface ion source. ^{74}Rb is easily surface ionizable, and previous measurements done by the ISAC yields group have demonstrated that the above combination provides more than an order of magnitude more ^{74}Rb than either UCx with 2 μA proton current, or Ta or ZCr with 100 μA proton current. Based on these previous measurements, the expected yields are on the order of 10^4 ions/s, with significant contamination from ^{74}Ga ($\sim 10^5$ ions/s), and ^{74m}Ga ($\sim 10^3$ ions/s). Although these contaminants cannot be separated from ^{74}Rb at the mass separator (a resolving power of ~ 4300 would be required), they can easily be cleaned from the MPET with dipole excitations at their respective reduced cyclotron frequencies prior to the mass measurement [4]. Alternatively, threshold charge breeding [14] can be used for isobar separation, which has been demonstrated at TITAN already for the neon-like shell closure of Ga and Ge ($q = 22+$) [17]; this technique could be used to separate ^{74}Rb^{27+} from its contaminants. For ^{74}Kr we request a 75 μA on a ZrC target with a FEBIAD ion source, which has been shown to produce $\sim 10^5$ ions/s, with $\sim 10^7$ ions/s contamination from both ^{74}Br and ^{74m}Br. This contamination can again be cleaned from the MPET with dipole excitations, or prior to the MPET with threshold charge breeding. We request a minimum of 3×10^3 ions/s of each ^{74}Rb and ^{74}Kr and we do not expect contamination to have an impact on our mass determination. The required yields and targets are provided in Table 2.

Because of ^{74}Rb's proximity to the drip-line it has both a short half-life ($t_{1/2} = 65$ ms) and relatively modest yields from the ISAC target station (100 times less than its neighbour ^{75}Rb). These two factors limit the excitation time of the ions in the MPET and also the number of ions that can be measured, making a precision measurement of its mass the most challenging aspect of this proposal. TITAN has explored charge breeding as an opportunity to boost the precision of ICR-TOF technique, sending ^{74}Rb ions into the EBIT and increasing their charge state prior to mass measurement. This was previously done at TITAN with charge state 8+, and a mass uncertainty of 81 ppb was obtained in only 22 hours [15]. When compared with the results from ISOLTRAP, 53 ppb from three different measurement campaigns [22, 25, 26], it becomes apparent how advantageous HCI measurements are for reducing the uncertainty. The new measurement of ^{74}Rb will be made with higher charge states, in the 19-27+ range, with higher statistics (see section (e)), and with better efficiencies at the TITAN facility to reach our target precision of less than $\delta m < 500$ eV (7 ppb or a Q_{EC}-value of less than 700 eV). This will be assisted by threshold charge breeding to the neon-like shell closure ($q = 27+$ for Rb), which not only provides isobarically clean beam, but also maximizes the population of a single charge state as seen in Figure 6. A calculation that considers the decay during charge breeding and the population of a single charge state under various charge breeding conditions provides insight to maximize the precision gained using highly charged ions by introducing an effective precision gain factor G_{HCI} (see [44] for a detailed discussion of G_{HCI} and [14] where G_{HCI} is considered for the case of ^{74}Rb).

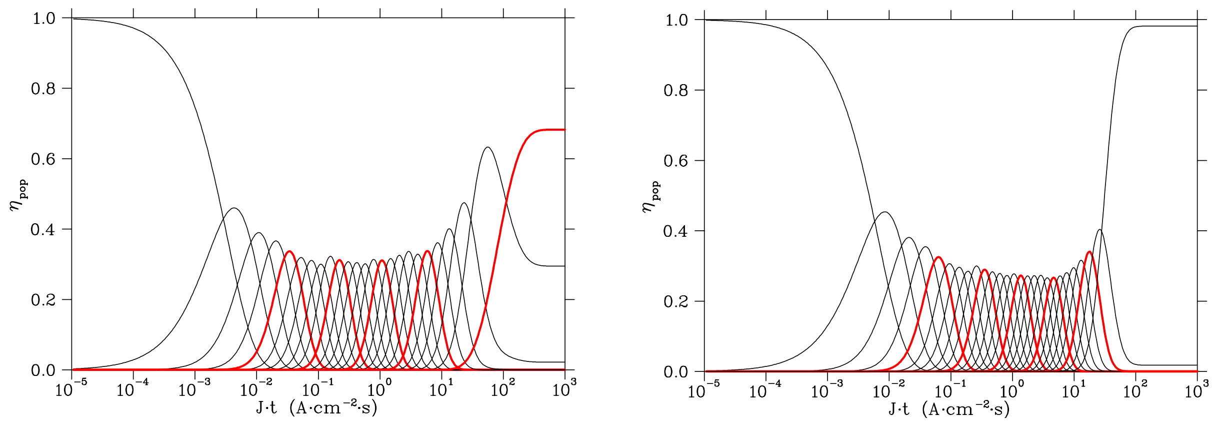

Figure 6: Simulated charge state evolution of Rb in an electron beam. The process evolves with time and with the electron beam current density (here in $A \cdot cm^{-2}$). Left: an electron beam energy of 1.2 keV populates many charge states at intermediary $J \cdot t$ and an equilibrium charge state distribution spread between 23-25+ for $J \cdot t \to \infty$. Right: the threshold of ionizing neon-like Rb produces a similar intermediate charge state distribution, but produces an equilibrium distribution of almost exclusively 27+ for $J \cdot t \to \infty$.

TITAN has already demonstrated its capabilities in precision mass measurements with HCI in the aforementioned ^{74}Rb measurement; however, there have been a series of improvements to the system that will allow us to reach the desired ppb precision stated in this new proposal. Extensive work has been done to improve and understand the efficiency of bunching in the RFQ, resulting to typically $\sim$ 15% transmission, as compared with $\sim$0.1% previously. The electron beam current has been increased by an order of magnitude (from 10 to 100 mA) allowing faster charge breeding and higher charge states to be obtained and resulting in higher precision for the ICR-TOF technique. Simulations and optimization of the EBIT settings have been performed to improve the electron impact ionization and recombination conditions in the EBIT, resulting in narrower charge state distributions and thus a higher population in a single charge state (see Figure 6(a) and 6(b)). TITAN is ready to perform these measurements on charge states up to 19+, taking advantage of the Ar-like shell closure for charge breeding. In order to pursue the full advantages of the precision and efficiencies gained at the 27+ Ne-like shell closure, further improvements to the current density and to the MPET vacuum are required and are currently under way.

(c) Experimental equipment

The TITAN facility, as described in section (b), will be required for the experiment, in addition to the ISAC yield station to determine yields of ^{74}Rb and ^{74}Kr and their respective isobaric contaminants.

Furthermore, use of the surface ion source and FEBIAD source will be required for ^{74}Rb and ^{74}Kr, respectively. A cooler Penning trap or multi-reflection time-of-flight trap, both under construction for TITAN, could be involved at the later stage of the proposed experiment.

(d) Readiness

The TITAN setup is operational and ready to perform the measurements as outlined above. In order to optimize the system a minimum of 2 weeks notice is required.

(e) Beam time required

The beam time required for the precision measurement of ^{74}Rb and ^{74}Kr is dependent on a variety of parameters such as the desired precision, yields, total TITAN efficiency, the charge state, and the excitation time. Based on the current TITAN set-up we expect efficiencies for:

- RFQ buncher and cooler: $\sim 15\%$
- EBIT injection, breeding, and extraction: $\sim 10\%$
- Populating a specific charge state: $\sim$10-65%, up to $\sim 95\%$ for threshold charge breeding
- HCI ion transport: $\sim 70\%$
- MPET capture of HCI: $\sim 10\%$
- Detection: $\sim 80\%$
- Decay survival fraction (total $t_{cycle} \leq 2.2t_{1/2}$): $\sim 22\%$

Considering the above efficiencies, measurements in charge states 19-27+, and the required value of 3×10^3 ions/s delivered to the TITAN RFQ, we require enough shifts to perform reference measurements, to reduce the statistical uncertainty, and to rule out systematic effects to the required ppb level. With the goal of less than 700 eV in the Q_{EC}-value, we require 1.5 shifts for set-up and 3.5 shifts for each ^{74}Rb and ^{74}Kr, or a total of 10 shifts. Additionally, we request ^{74}Ge from OLIS during the online beamtime as well as each time 1 OLIS shift for setup prior to the ISAC beam of ^{74}Rb and ^{74}Kr.

(f) Data analysis

The data evaluation methods are well developed for the TITAN mass spectrometer system, and all the necessary software tools are available.

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a. Articles submitted to refereed journals

In-trap decay spectroscopy towards the determination of $M^{2\nu\beta\beta}$
T. Brunner, A. Lapierre, C. Andreoiu, M. Brodeur, P. Delheji, **S. Ettenauer**, D. Frekers, A.A. Gallant, R. Gernhäuser, A. Grossheim, R. Krücken, D. Lunney, R. Ringle, M.C. Simon, V.V. Simon, S.K.L. Suje, K. Zuber, and J. Dilling
submitted European Journal of Physics A

Electron-Capture Branching Ratio Measurements of Odd-Odd Intermediate Nuclei in Double-Beta Decay at the TITAN Facility
A. Lennarz, A. Grossheim, F. Jang, C. Andreoiu, T. Brunner, A. Chaudhuri, U. Chowdhury, P. Delheij, J. Dilling, **S. Ettenauer**, D. Frekers, A.T. Gallant, G. Gwinner, A.A. Kwiatkowski, T. Ma, E. Mané, M.R. Pearson, B.E. Schultz, M.C. Simon, V.V. Simon
submitted to Hyperfine Interactions

An investigation of accuracy of the TITAN Penning-trap mass spectrometer during on-line experiment
A Chaudhuri, U Chowdhury, **S Ettenauer**, A T Gallant, A A Kwiatkowski, A Lennarz, **T D Macdonald**, B E Schultz, V V Simon, M C Simon, and J Dilling.
submitted to European Journal of Physics D

An ion trap for accurate mass measurements of ms-half-life nuclides
A Chaudhuri, C Andreoiu, M Brodeur, T Brunner, U Chowdhury, **S Ettenauer**, A T Gallant, A Grossheim, G Gwinner, R Klawitter, A A Kwiatkowski, K G Leach, A Lennarz, D Lunney, **T D Macdonald**, R Ringle, B E Schultz, V V Simon, M C Simon, and J Dilling..
submitted to Applied Physics B

b. Articles published or accepted in refereed journals

Charge breeding rare isotopes for high precision mass measurements : challenges and opportunities
M C Simon, **T D Macdonald**, J C Bale, U Chowdhury, B Eberhardt, M Eibach, A T Gallant, F Jang, A Lennarz, M Luichtl, T Ma, D Robertson, V V Simon, C Andreoiu, M Brodeur, T Brunner, A Chaudhuri, J R Crespo L´opez-Urrutia, P Delheij, **S Ettenauer**, D Frekers, A Grossheim, G Gwinner, A A Kwiatkowski, A Lapierre, E Man´e, M R Pearson, R Ringle, B E Schultz, and J Dilling..
Physica Scripta, 2013 - accepted for publication

Cooling of highly-charged short-lived ions for precision mass spectrometry at TITAN
B E Schultz, V V Simon, C Andreoiu, A Chaudhuri, A T Gallant, A A Kwiatkowski, **T D Macdonald**, M C Simon, J Dilling, and G Gwinner..
Physica Scripta, 2013 - accepted for publication

Mass Measurements of Singly and Highly Charged Radioactive Ions at TITAN : A New Q-value Measurement of ^{10}C
Anna A Kwiatkowski, Ankur Chaudhuri, Usman Chowdhury, Aaron T Gallant, **Tegan D Macdonald**, Bradley E Schultz, Martin C Simon, and Jens Dilling.
Annalen der Physik, 2013 - accepted for publication

Precision Mass Measurements at TITAN with Radioactive Ions
A A Kwiatkowski, **T D Macdonald**, C Andreoiu, J C Bale, T Brunner, A Chaudhuri, U Chowdhury, **S Ettenauer**, A T Gallant, A Grossheim, A Lennarz, E Man ́e, M R Pearson, B E Schultz, M C Simon, V V Simon, and J Dilling.
Nucl. Instr. and Meth. B, in press

Advances in precision, resolution, and separation techniques with radioactive, highly charged ions for Penning trap mass measurements
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