TRIUMF EEC NEW RESEARCH PROPOSAL

Detailed Statement of Proposed Research for Experiment # S1189

Please use text in 12 point font and add extra pages. Note, however, that the EEC Committees strongly recommend that you limit your submissions, including figures and tables, to no more than 4 pages for the MMSEEC and 10 pages for the SAPEEC. The following information should be included:

(a) **Scientific value of the experiment**: Describe the importance of the experiment and its relation to previous work and to theory. All competitive measurements at other laboratories should be mentioned. Include examples of the best available theoretical calculations with which the data will be compared.

(b) **Description of the experiment**: Techniques to be used, scale drawing of the apparatus, measurements to be made, data rates and background expected, sources of systematic error, results and precision anticipated. Compare this precision with that obtained in previous work and discuss its significance in regard to constraining theory. Give a precise list of targets to be used in order of their priority.

(c) **Experimental equipment**: Describe the purpose of all major equipment to be used.
Details of all equipment and services to be supplied by TRIUMF must be provided separately on the Technical Review Form available from the Science Division Office.

(d) **Readiness**: Provide a schedule for assembly, construction and testing of equipment. Include equipment to be provided by TRIUMF.

(e) **Beam time required**: State in terms of number of 12-hour shifts. Show details of the beam time estimates, indicate whether prime-user or parasitic time is involved, and distinguish time required for test and adjustment of apparatus.

(f) **Data analysis**: Give details and state what data processing facilities are to be provided by TRIUMF.

For CMMS Experiments, make sure that your detailed information includes:

- a concise summary of the scientific problem under investigation, with appropriate literature references;
- clear justification for the proposed experiments and, specifically, a justification for using μSR/β-NMR techniques
- a description of the experimental techniques to be used, naming the μSR/β-NMR spectrometer(s) or ISAC facilities to be used;
- an analysis of beam time requirements, including a prioritized list of samples;
- Groups with multiple experiments should list all concurrent experiments and proposals, outside of TRIUMF, with an indication of how the personnel effort is to be divided between these activities.

For SAP Experiments, make sure that your detailed information includes:

- an indication of whether you are pursuing Stage 2 approval (beam allocation) at this time;
- if you are, sufficient technical information to demonstrate feasibility to start within two years;
- a clear identification of the facilities to be used and the equipment and services to be supplied by TRIUMF.

a.) Scientific importance of measurements of the masses of ^{70,71}Kr and ^{70}Br

The rapid proton capture process (rp-process) is believed to drive type I X-ray bursts in accreting neutron stars, producing trans-ferric elements [1,2]. The rp-process proceeds along isotonic chains until proton capture is inhibited by proton emission or photodisintegration, at which point the process is delayed waiting for β-decay to proceed along the next isotonic chain. At certain points the process encounters isotonic chains terminated by isotopes with particularly long β-decay half-lives. These are the waiting point nuclei.

The even-even N=Z nuclei ^{64}Ge, ^{68}Se and ^{72}Kr each have long β -decay half-lives compared to the rp-process timescale of 10 – 100 s. These waiting point nuclei could strongly impede the progress of the rp-process, leading to extended tails in X-ray burst light curves [3]. It is important to understand the effective lifetimes of these waiting points in order to be able to determine astrophysical sites at which the rp-process occurs through comparison of measured and calculated light curves.

In the case of ^{68}Se, due to the highly proton unbound ^{69}Br, an equilibrium is reached: ^{68}Se(p,γ)^{69}Br(γ,p)^{68}Se. There are two paths out of this equilibrium state – a slow leak via β-decay of ^{68}Se and sequential 2p-capture, ^{68}Se(p,γ)^{69}Br(p,γ)^{70}Kr. The rate of this reaction is determined by the Saha equation, which has an exponential dependence on the masses of the nuclei involved. As such, it is of great importance that the nuclear masses be known well, preferably $\delta m < 10$ keV. Recently, the masses of $^{68, 69, 70}$Se have been measured to a level of $\delta m << 10$ keV [4,5]. This allows for the masses of ^{69}Br and ^{70}Kr to be calculated via Coulomb Displacement Energy methods with estimated uncertainties of 100 keV [6]. This has allowed the uncertainty in the effective lifetime of ^{68}Se to be reduced; however, it still has a fairly large uncertainty, as shown in Fig. 1. The direct measurement of the mass of ^{70}Kr would greatly improve the precision of the effective lifetime of ^{68}Se and lead to better understanding of the nature of X-ray burst phenomena.

^{70}Kr has a short but uncertain β-decay lifetime of 57(21) ms [7]. At high stellar temperatures, ^{70}Kr can undergo photodisintegration – ^{70}Kr(γ,p)^{69}Br(γ,p)^{68}Se – and come into equilibrium with ^{68}Se. In such a situation, the effective lifetime of the ^{68}Se is proportional to the β-decay lifetime of ^{70}Kr [7]. The temperature at which this effect begins to become relevant depends on $S_p(^{70}\text{Kr})$, but is approximately T = 1.3GK as indicated by the position of the minimum in Fig. 1.

The effect of the β-decay lifetime of ^{70}Kr on the effective lifetime of ^{68}Se at a stellar temperature of T = 1.3GK can be seen Fig. 2, from [8], for 1.33 MeV ≤ $Q_{2p}(^{68}\text{Se})$ ≤ 1.95 MeV. At the larger value $t_{1/2}(^{70}\text{Kr})$ is insignificant, while at the lesser value it is highly important. The present best estimate of $Q_{2p}(^{68}\text{Se})$ = 1.77(25) MeV [4-6] lies between these two calculations, indicating that $t_{1/2}(^{70}\text{Kr})$ may have a large impact in the effective lifetime of ^{68}Se at T = 1.3GK. At higher temperatures the effect will become even stronger. As X-ray bursts typically achieve peak temperatures of 1.5 – 2.0GK, an accurate measure of $t_{1/2}(^{70}\text{Kr})$ is

very important to X-ray burst simulations. Thus an improvement in $t_{1/2}(^{70}Kr)$ could be quite valuable.

Additionally, the masses of of ^{70}Br and ^{71}Kr hold some importance for understanding the pathway of the rp-process in this region. A partial reaction network for this region is given in Fig. 3, from which it can be seen that the flow can proceed via the β-decay of ^{70}Br or ^{71}Kr. The flow ratio for these two paths is determined by $S_p(^{70}Br)$, which requires precise measurements of the masses of ^{70}Br and ^{71}Kr. While the isomeric state of ^{70}Br has been measured to $\delta m \sim 10$ keV at NSCL [4], the ground state mass is presently determined indirectly. Additionally, the mass for ^{71}Kr has a 650 keV uncertainty and has been measured via the β-decay endpoint method [9].

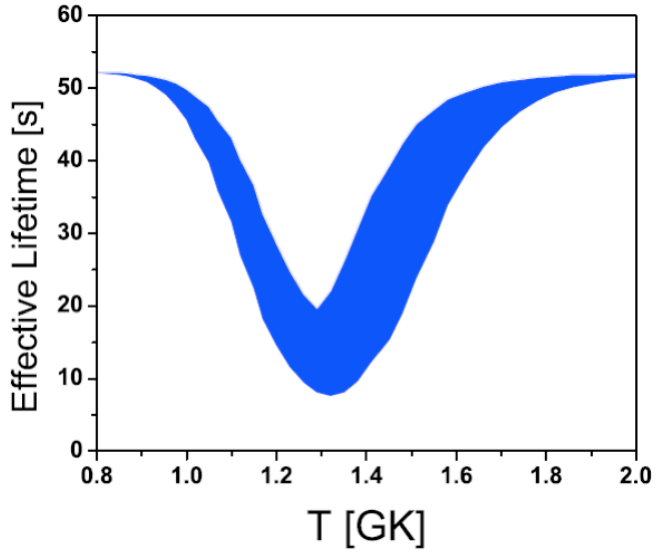

Figure 1: Effective lifetime of ^{68}Se calculated using data from [5,6,8] assuming $t_{1/2}(^{70}Kr) = 57$ ms.

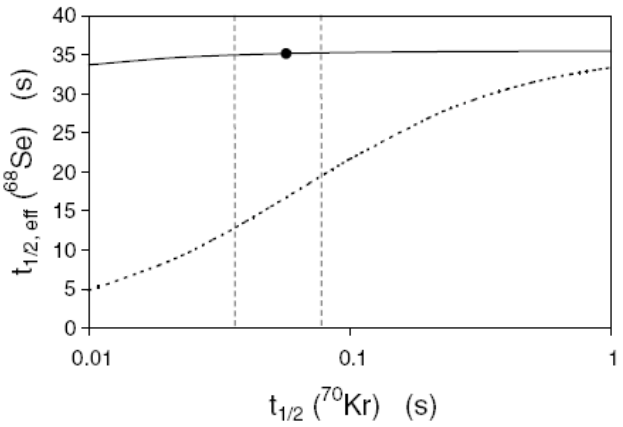

Figure 2: The effective stellar haf-life of ^{68}Se as a function of the half-life of ^{70}Kr for two values of $Q_{2p}(^{68}Se)$: 1.95 MeV (dotted curve) and 1.33 MeV (solid curve). The data point shown indicates the known half-life of ^{70}Kr with its uncertainty represented by the vertical dashed lines.

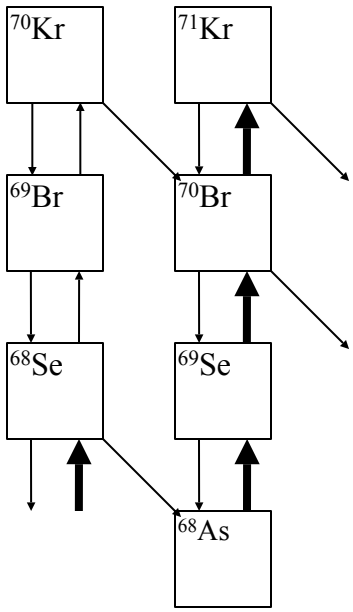

Figure 3: Partial reaction network showing the rp-process pathway passing through ^{68}Se. Vertical arrows represent (p,γ) and (γ,p) reactions, while diagonal lines represent β-decay.

b.) Description of experiment

Beams of neutron-deficient Kr and Br via spallation reactions have been produced at ISOLDE using a Nb target [7]. To date, beams of ^{70,71}Kr and ^{70}Br have not been developed at TRIUMF, but beams of other noble gases, such as He and Ne, are now routinely available using the FEBIAD ion source. It is not foreseen that Kr should cause any additional difficulties.

The mass measurements will be performed using the TITAN facility. Isotope beams delivered by ISAC at an energy of ≈ 30 keV will be brought to rest in a linear Paul trap which serves as a cooler and buncher (RFQ) which is maintained at a potential near the beam energy. The beam is cooled to thermal temperatures by collisions with a buffer gas, typically He, and trapped in a potential minimum created by a DC gradient in the RFQ. The DC beam is then converted to a pulsed beam and brought to ground with 1 keV of energy via a pulsed drift tube located directly after the RFQ.

In expectation of very low yields of the desired beams, and modest desired relative mass precisions of the order $\delta m/m \approx 10^{-7}$, charge breeding with the Electron Beam Ion Trap (EBIT) will not be required. Instead, the ion bunch will be transported directly from the RFQ into a high-precision Penning trap mass spectrometer (MPET), where cleaning of isobaric contamination will take place, if necessary, before the mass measurement is performed. Between the RFQ and the MPET there is a time-of-flight gate (TOFG), used for non-isobaric purification in flight, and a passivated implanted planar silicon (PIPS) detector, used for verifying the presence of radioactive ions delivered by the RFQ. A schematic of the system as it will be used is given in Fig. 4. For general system tuning, and identification of possible molecule formation within the RFQ, we would require Kr and Br isotope beams with higher yields. Listed below are some properties of the possible isotopes to be measured. A "#" denotes that the mass value is extrapolated. It should also be noted that the mass of ^{70m}Br was measured with LEBIT [10] from which the ground state mass can be determined, but is not yet published.

Nucleus	$T_{1/2}$	Mass Uncertainty Goal [keV]	Current Mass Uncertainty [keV]
^{70}Br	79.1 ± 0.8 ms	10	310# [11]
^{71}Br	21.4 ± 0.6 s	10	570 [11]
^{72}Br	78.6 ± 2.4 s	10	60 [11]
^{70}Kr	57 ± 21 ms	10	390# [11]
^{71}Kr	100 ± 3 ms	10	650 [11]

Nucleus	$T_{1/2}$	Mass Uncertainty Goal [keV]	Current Mass Uncertainty [keV]
^{72}Kr	17.16 ± 0.18 s	10	8 [11]

The TITAN facility is the ideal location for measuring the masses of very short-lived isotopes ($T_{1/2} \geq 1$ ms) to high precision due to a fast repetition cycle and high resolving power achievable with a Penning trap mass spectrometer. A 50 Hz repetition cycle was demonstrated with the mass measurement of the short-lived halo nucleus, ^{11}Li ($T_{1/2} \approx 9$ ms). Once the ions are trapped in the Penning trap using a dynamic capture process, a time-of-flight resonance detection technique [12] is used to determine the ions' cyclotron frequency, given by

$$\nu_c = \frac{1}{2\pi}\frac{qB}{m}.$$

Here, *q* is the charge of the ion, *B* is the strength of the magnetic field (≈ 3.7 T for the MPET), and *m* is the mass of the ion. By measuring ν_c it is possible to determine *m*, provided that the charge state is and magnetic field strength is known. To precisely determine *B*, a high-precision mass measurement of a well-known stable species is required. The electrode structure of the MPET is used to generate a quadrupolar electric field and the resulting ion motion in the trap consists of three independent eigenmotions [13], two of which are in the radial plane and one of which is along the axis of the trap. The two radial motions are the reduced cyclotron motion, with frequency ν_+, and the magnetron motion with frequency ν_-. The two radial motions are related to the cyclotron frequency by $\nu_c = \nu_- + \nu_+$. The ions' cyclotron frequency is determined by applying a quadrupolar RF field at frequency ν_c, which causes a periodic conversion of one radial motion to the other. The ions begin in a state of nearly pure magnetron motion. The application of a quadrupolar RF field at frequency ν_c for a chosen time, T_{RF}, and amplitude, A_{RF}, called a π-pulse, will fully convert the magnetron motion into cyclotron motion. This conversion is accompanied by a drastic increase in kinetic energy as $\nu_+ \gg \nu_-$. The ions are then ejected from the trap. As they travel out of the magnetic field to a microchannel plate (MCP) detector at the end of the system, the kinetic energy associated with the radial motion, gained during the excitation, is converted into axial kinetic energy and a reduced time of flight to the detector is observed. By scanning over a frequency rage around ν_c a cyclotron resonance is measured (see Fig. 4). For a given resonance curve the relative mass precision is given by

$$\frac{\delta m}{m} \propto \frac{1}{\nu_c \cdot T_{RF} \cdot \sqrt{N}}.$$

Here *N* is the number of measured ions. An optimal precision is achieved when $T_{RF} \approx 2T_{1/2}$, in the absence of other contaminating ions in the trap.

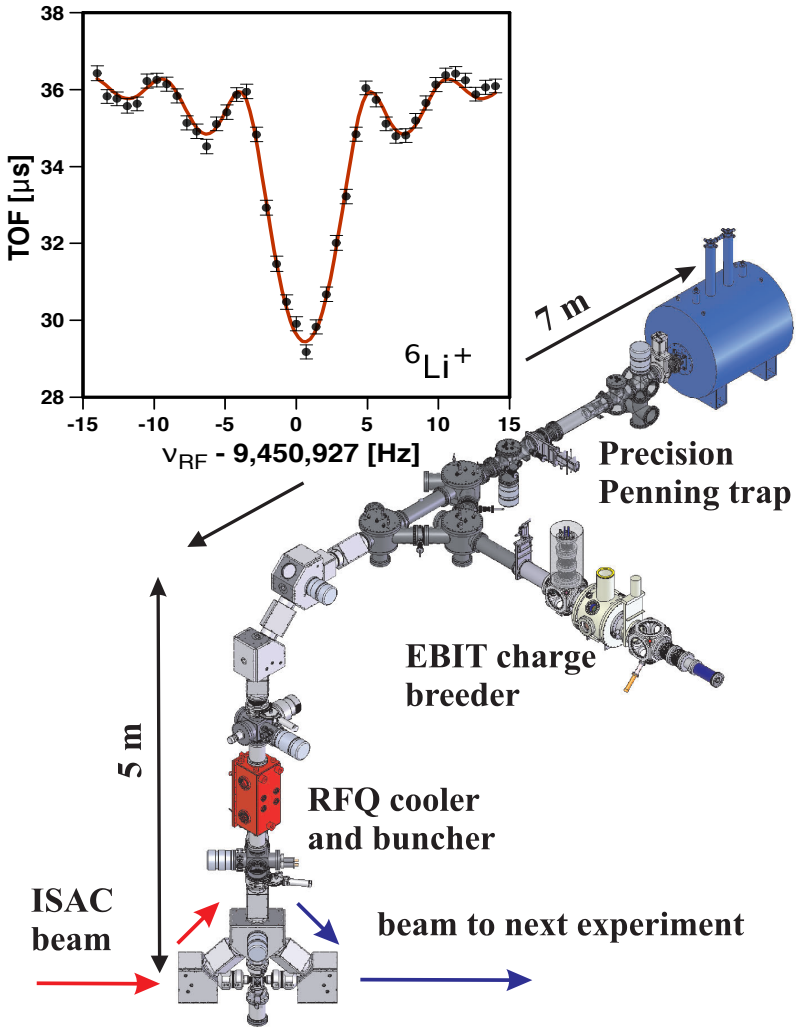

Fig. 4: Schematic drawing of the TITAN facility. Inset shows a typical offline time-of-flight resonance curve of $^6Li^+$. The solid line is a fit of the theoretical curve to the data.

Previous experiments and thorough systematic studies with stable ions have taught us what to expect in terms of efficiency from the TITAN facility. A breakdown of the relevant efficiencies are:

1.	Transport efficiency of the RFQ	≈ 60%
2.	Dynamic capture in the MPET	≈ 100 % (for 10-15 V deep trap)
3.	Decay losses during measurement	≈ 50 % * T_{RF} (in units of $T_{1/2}$)

4. Detection efficiency of MCP ≈ 80 %

Other as yet unknown sources of losses include possible distribution of the ion of interest over several molecular sidebands. This will need to be determined on an element-by-element basis, but is mitigated by using ultra-high purity He gas in the RFQ.

Isobaric contaminants to be cleaned away in the MPET should be, at most, a factor of 100 more numerous than the isotope of interest. A known contaminant can be cleaned away with ≈ 100 % efficiency at the cost of additional measurement time. The tables below lists the closest possible contaminants and the resolving power necessary to separate them from the beams of interest.

Contaminant [^{70}Kr]	Mass Excess [keV]	Required Resolving Power
^{70}Br	-51430 ± 310	6700
^{70}Se	-62050 ± 60	3200
^{70}As	-64340 ± 50	2900
^{70}Ge	-70563.1 ± 1.0	2300

Contaminant [^{70}Br]	Mass Excess [keV]	Required Resolving Power
^{70}Kr	-41680 ± 390	6700
^{70}Se	-62050 ± 60	6100
^{70}As	-64340 ± 50	5100
^{70}Ge	-70563.1 ± 1.0	3400

Contaminant [^{71}Kr]	Mass Excess [keV]	Required Resolving Power
^{71}Br	-57060 ± 570	6400
^{71}Se	-63120 ± 30	4000
^{71}As	-67894 ± 4	3100
^{71}Ge	-69907.7 ± 1.0	2800

c.) Experimental equipment

All necessary equipment is part of the TITAN facility. No external equipment will be required.

d.) Readiness

The TITAN facility is fully commissioned and is operated on a daily basis for systematic studies on stable isotopes. The experiment can be run at any time with a minimal amount (≈ 1 week) of forewarning.

We are seeking stage 2 approval at this time.

e.) Beam time required

Nothing is yet known concerning the yields of the Kr and Br isotopes of interest, but delivery of other noble gases, such as He and Ne, is now routinely achieved in conjunction with the FEBIAD ion source. Therefore, delivery of Kr isotopes is not foreseen to present any problems. Assuming a delivered yield of 1 pps, the efficiencies mentioned above, and 1000 ions for a typical time-of-flight spectrum the time required for one measurement would be ≈ 140 minutes for a measurement with an excitation length of $T_{RF} = 2T_{1/2}$. Individual time-of-flight spectra will yield relative mass precisions of $\delta m/m \approx 3.4 \times 10^{-7}$ for ^{70}Kr, $\delta m/m \approx 2.4 \times 10^{-7}$ for ^{70}Br, and 2×10^{-7} for ^{71}Kr. Multiple measurements of primary nuclei will be required to reach the goal of $\delta m/m \approx 1 \times 10^{-7}$.

Six shifts should be sufficient to measure ^{70,71}Kr and ^{70}Br once they've been delivered. Another four shifts would be used for the initial system tuning and measurement of preliminary isotopes. An additional six shifts would be necessary for beam development, for a total of 16 shifts. It is not necessary that both elements are measured during the same experiment, but may split up for added flexibility and off-line optimizations. It is envisaged that we would be the prime user, and not operate in parasitic mode. Although if extra shifts are available during beam development studies, and Br or Kr are delivered, the possible chemistry-related effects could be determined beforehand.

f.) Data analysis

All data analysis software and necessary computers are present at the TITAN facility.

References

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