TRIUMF - EEC SUBMISSION EEC meeting: 200807S *Original Proposal*	TRIUMF	**Exp. No.** S1194 - *Pending (Stage 1)* **Date Submitted:** 2008-06-10 09:06:53

Title of Experiment:

Measuring the masses of ^{65}As and ^{66}Se with TITAN

Name of group:

Spokesperson(s) for Group

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Current Members of Group:
(name, institution, status, % of research time devoted to experiment)

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J. Dilling	TRIUMF	Research Scientist	10%
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Beam Shift Requests:

14 shifts on: TITAN

Basic Information:

Date submitted: 2008-06-10 09:06:53

Date experiment ready:

Summary: Type I X-ray bursts (XRBs) result from thermonuclear runaways in hydrogen- and/or helium-rich material accreted on to the surface of a neutron star in a low-mass X-ray binary. Because of the extreme conditions during an XRB, the flow of material is driven towards the proton drip-line and to high masses. The large number of reaction rates involved in XRB nucleosynthesis means it is important to identify which of these rates significantly affect XRB properties such as nucleosynthesis and light curves. Reducing the uncertainties of such rates can help to expose weaknesses in the astrophysical assumptions of different models, ideally leading to convergence of XRB model predictions. A study of the sensitivity of XRB nucleosynthesis to uncertainties in the input nuclear physics revealed a very limited number of reaction-rates that strongly influence XRB yields. The rate of the ^{65}As(p,γ) ^{66}Se reaction was found to be one of the most important in this study, affecting the production of isotopes from ^{64}Zn to ^{104}Ag by at least a factor of 2 in the majority of models. Since rate calculations depend critically upon reaction Q-values, it is of vital importance to measure the masses of ^{65}As and ^{66}Se. We propose to perform these mass measurements using the TITAN facility. The TITAN facility is the ideal location for measuring the masses of very short-lived isotopes to high precision due to a fast repetition cycle and high resolving power achievable with a Penning trap mass spectrometer.

Plain Text Summary: Type I X-ray bursts (XRBs) result from thermonuclear runaways in hydrogen- and/or helium-rich material accreted on to the surface of a neutron star in a low-mass X-ray binary. The flow of material depends on the reaction rates and masses of the nuclei involved. The masses of 65As and 66Se are two important parameters in this context. We propose to perform these mass measurements using the TITAN Penning trap facility.

Summary of Experiment Results:

Primary Beamline: isac2a

ISAC Facilities

ISAC Facility: TITAN

ISAC-I Facility:

ISAC-II Facility:

Secondary Beam

Isotope: 65-68As,66-69Se

Energy: 30

Intensity Requested: 100

Minimum Intensity: 1

Maximum Intensity: --

Energy Units:

Energy spread-maximum: --

Time spread-maximum: --

Angular Divergence: --

Spot Size: --

Charge Constraints: --

Beam Purity: 1

Special Characteristics: --

Experiment Support

Beam Diagnostics Required:

Signals for Beam Tuning:

DAQ Support: TITAN DAQ existing

TRIUMF Support: Beam development

NSERC:

NSERC:

Other Funding:

Muon Justification:

Safety Issues: Standard TITAN procedures will be observed.

Measuring the masses of ^{65}As and ^{66}Se with TITAN

(a) **Scientific value of the experiment:**

Type I X-ray bursts (XRBs) result from thermonuclear runaways in hydrogen- and/or helium-rich material accreted on to the surface of a neutron star in a low-mass X-ray binary. Over 80 such bursting systems have been observed in our Galaxy (e.g. Strohmayer and Bildsten 2006; Schatz and Rehm 2006; Galloway et al. 2006). Because of the extreme conditions during an XRB ($T_{peak} > 109$ K, $\rho \approx 106$ g/cm^3), the flow of material is driven towards the proton drip-line and to high masses (as far as ^{126}Xe in Koike et al. 2004, but see also Schatz et al. 2001 and Woosley et al. 2004) through the αp and rp processes (Wallace and Woosley 1981; Schatz et al. 1998).

Because of the large number of reaction rates involved in XRB nucleosynthesis (most of which can only be estimated theoretically due to lack of experimental information), it is important to identify which of these rates significantly affect XRB properties such as nucleosynthesis and light curves. Reducing the uncertainties of such rates can help to expose weaknesses in the astrophysical assumptions of different models, ideally leading to convergence of XRB model predictions. Characteristics of the observed XRB light curves then provide direct constraints on hydrodynamic models. As well, the ashes of XRBs may show gravitationally-redshifted atomic absorption lines from the neutron star surface, observable through high-resolution X-ray spectra (Cottam et al. 2002; Bildsten et al. 2003; Chang et al. 2005; Weinberg et al. 2006). Such features would directly probe XRB nucleosynthesis.

Most attempts to examine the effects of rate uncertainties in XRBs have either varied a few specific reactions individually (Iliadis et al. 1999; Thielemann et al. 2001; Fisker et al. 2004, 2006, 2007), or varied groups or entire libraries of rates (Wallace and Woosley 1981; Schatz et al. 1998; Koike et al. 1999; Woosley et al. 2004). Progress towards more systematic studies of the impact of nuclear physics uncertainties in XRB models has been reported in Amthor et al. (2006) and Roberts et al. (2006). Note that hydrodynamic simulations are computationally prohibitive for large-scale sensitivity studies; hence, onezone post-processing calculations are generally used.

To help guide relevant future experiments, Parikh et al. (2008) performed a comprehensive series of investigations into the sensitivity of XRB nucleosynthesis to uncertainties in the input nuclear physics. They used a post-processing approach in conjunction with a diverse set of thermodynamic histories and initial conditions (Models) to sample the parameter space of XRB nucleosynthesis calculations. Through complementary studies in which rates of over 2000 nuclear processes were both individually varied within limits as well as simultaneously varied using a Monte Carlo technique, they identified a very limited number of reaction-rates that strongly influenced XRB yields. The rate of the ^{65}As(p,γ)^{66}Se reaction was found to be one of the most important in this study, affecting the production of isotopes from ^{64}Zn – ^{104}Ag by at least a factor of 2 in the majority of Models, when its (theoretical) rate was varied by an overall factor of 10 up and down. (Through comparison of different theoretical rates, Parikh et al. found support for attributing a factor of ≈10 uncertainty to theoretical rates over XRB temperatures as opposed to a significantly larger factor (e.g. Amthor et al. 2006).) Moreover, variation of this rate affected isotopes with the largest post-burst yields in many of the Models, demonstrating the possible importance of this rate for the composition of the neutron star crust.

The importance of the ^{65}As(p,γ)^{66}Se reaction-rate had been expected (e.g. Schatz et al. 1998) due to its bridging effect on the well-known ^{64}Ge 'waiting point' (see below). No experimental information is available to allow calculation of this reaction-rate; indeed, not even the masses of ^{65}As and ^{66}Se have been measured (they have been estimated as $\Delta(^{65}\text{As}) = -46981(302)$ keV and $\Delta(^{66}\text{Se}) = -41722(298)$ keV in Audi et al. (2003), where Δ is the mass excess). Since rate calculations depend critically upon reaction Q-values, it is of vital importance to measure the masses of ^{65}As ($t_{1/2} = 128$ ms) and ^{66}Se ($t_{1/2} = 33$ ms) so as to better determine the ^{65}As(p,γ)^{66}Se rate.

Parikh et al. (2008) also explored the effects of uncertainties in reaction Q-values on XRB yields. Reactions with small ($\leq$ MeV) Q-values are of particular interest as they quickly achieve equilibrium between the forward and reverse processes in XRB conditions, and therefore represent waiting points during a burst for a continuous reaction flow toward heavier-mass nuclei. To determine the most influential Q-value uncertainties, they examined the effects of individually varying all reactions with $Q < 1$ MeV in their network, by the respective Q-value uncertainties as given in Audi et al. (2003), for all Models. This involved re-calculating reverse rates for these reactions using $Q + \Delta Q$ and $Q - \Delta Q$. A total of 111 reactions were varied in this manner. Note that experimental information for most of these reaction Q-values is not available; for these cases, they adopted the extrapolated values (and uncertainties) of Audi et al. (2003). They found that the uncertainty in the Q-value of the ^{64}Ge(p,γ)^{65}As reaction is overwhelmingly the most critical in determining XRB yields, affecting the yields of isotopes from ^{64}Zn – ^{104}Ag by a factor of 2 or more, in most of the Models (Parikh et al., in preparation). The nuclear energy generation was found to be affected by this Q-value as well. The mass of ^{64}Ge has been measured (Clark et al. 2007; Schury et al. 2007), but the mass of ^{65}As has only been estimated (see above). The principal waitingpoints in XRBs are thought to be ^{64}Ge, ^{68}Se and ^{72}Kr (e.g. Schatz et al. 1998), and the studies of Parikh et al. indicate that the Q-value of the ^{64}Ge(p,γ)^{65}As reaction is perhaps the most significant.

To better constrain predictions of nucleosynthesis in Type I X-ray bursts, then, we propose to measure the masses of ^{65}As and ^{66}Se at TITAN.

(b) **Description of the experiment:**

Beams of As and Se can be produced using a ZrO_2 target. To date, ^{65}As and ^{66}Se have not been observed at TRIUMF or ISOLDE. Therefore, a significant amount of time will have to be devoted to beam development. Since neither As or Se is a candidate for laser ionization, and cannot be surface ionized, the FEBIAD ion source will be required.

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 $\frac{\delta m}{m} \approx 10^{-7}$, 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. 1. For general system tuning, and identification of possible molecule formation within the RFQ, we would require As and Se isotope beams with higher yields. Table 1 lists some properties of the possible isotopes to be measured.

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

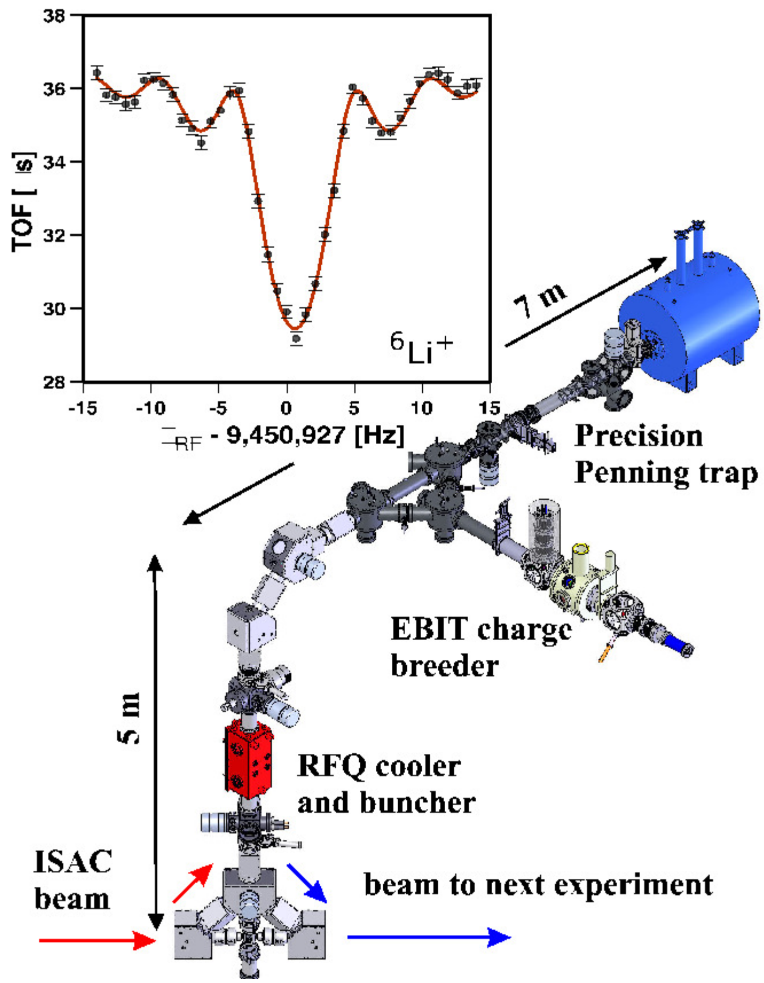

Figure 1: Schematic drawing of the TITAN facility. Inset shows a typical offline time-of-flight resonance curve of $^6Li^+$. The solid line is a fit of the theoretical curve to the data.

Table 1: List of some properties of the possible isotopes to be measured.

Nucleus	$t_{1/2}$	Mass uncertainty Goal [keV]	Mass uncertainty Current [keV]
^{68}As	111 ± 20 s	5	5.3 (Schury et al., 2007)
^{67}As	42.5 ± 1.2 s	5	1.1 (Schury et al., 2007)
^{66}As	95.77 ± 0.23 ms	5	30 (Schury et al., 2007)
^{65}As	170 ± 30 ms	5	300 (Wapstra et al., 2003)
^{69}Se	27.4 ± 0.2 s	5	1.5 (Schury et al., 2007)
^{68}Se	35.5 ± 0.7 s	5	30 (Wapstra et al., 2003)
^{67}Se	133 ± 11 ms	5	200 (Wapstra et al., 2003)
^{66}Se	33 ± 12 ms	5	300 (Audi et al., 2003)

Table 2: The closest possible contaminants and the resolving power necessary to separate them from the beam of interest.

Contaminant	Mass Excess [keV]	Required Resolving Power
^{65}Ge	-56410 ± 100	6500
^{65}Ga	-62657.2 ± 0.8	3900
^{65}Zn	-65911.6 ± 0.7	3200
^{66}As	-52018 ± 30	6000
^{66}Ge	-61607.0 ± 2.4	3100
^{66}Ga	-63724 ± 3	2800

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 (G. Bollen et al., 1990) is used to determine the ions' cyclotron frequency, given by

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

Here, q is 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 (König et al., 1995), 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. 1). For a given resonance curve the relative mass precision is given by

$$\frac{\delta m}{m} = \frac{1}{\nu_c \cdot T_{RF} \cdot \sqrt{N}} . \tag{2}$$

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.

(c) **Experimental equipment:**
The TITAN setup will be needed.

(d) **Readiness:**
The TITAN setup is currently in running mode. Target development is needed to provide the requested beams.

(e) **Beam time required:**
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 on the relevant efficiencies are:
1. Transport efficiency of the RFQ $\approx$ 60%
2. Dynamic capture in the MPET $\approx$ 100 % (for 10-15 V deep trap)
3. Decay losses during measurement $\approx$ 50 % * T_{RF} (in units of $t_{1/2}$)
4. Detection efficiency of MCP $\approx$ 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 $approx$ 100 % efficiency at the cost of additional measurement time. Table 2 lists the closest possible contaminants and the resolving power necessary to separate them from the beam of interest.
As nothing is yet known concerning the yields of the As and Se isotopes of interest, significant time will be required for beam development. 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 $\approx$ 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 $\frac{\delta m}{m} \approx 9 \cdot 10^{-8}$ for ^{65}As and $\frac{\delta m}{m} \approx 5 \cdot 10^{-7}$ for ^{66}Se. Multiple measurements of ^{66}Se will be required to reach the goal of $\frac{\delta m}{m} \approx 1 \cdot 10^{-7}$.
Four shifts should be sufficient to measure ^{65}As and ^{66}Se once they have 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 14 shifts. It is not necessary that both As and Se are measured during the same experiment, but may split up for added flexibility and off-line optimizations

(f) **Data analysis:**
All the necessary software tools are now operational for analyzing TITAN data.

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Spokesperson (A. Parikh) Publications List for Experiment # S1194

"The sensitivity of nucleosynthesis in Type I X-ray bursts to thermonuclear reaction rate variations" A. Parikh, J. José, F. Moreno and C. Iliadis, accepted for New Astron. Rev.

"The effect of variations in nuclear processes on Type I X-ray burst nucleosynthesis" A. Parikh, J. José, F. Moreno and C. Iliadis, accepted for Astrophys. J. Suppl.

"Nuclear structure relevant to neutrinoless double beta decay: ^{76}Ge and ^{76}Se" J. P. Schiffer, S. J. Freeman, J. A. Clark, C. Deibel, C. R. Fitzpatrick, S. Gros, A. Heinz, D. Hirata, C. L. Jiang, B. P. Kay, A. Parikh, P. D. Parker, K. E. Rehm, A. C. C. Villari, V. Werner and C. Wrede, Phys. Rev. Lett. **100**, 112501 (2008).

"High-j single particle neutron states outside the N=82 core" B. P. Kay, S. J. Freeman, J. P. Schiffer, J. A. Clark, C. Deibel, A. Heinz, A. Parikh, P.D. Parker, K. E. Rehm and C. Wrede, Phys. Lett. B **658**, 216 (2008).

"Measurement of ^{23}Mg(p,γ)^{24}Al resonance energies" D. W. Visser, C. Wrede, J. A. Caggiano, J. A. Clark, C. Deibel, R. Lewis, A. Parikh and P. D. Parker, Phys. Rev. C **76**, 065803 (2007).

"New ^{30}P(p,γ)^{31}S resonances and nucleosynthesis in oxygen-neon novae" C. Wrede, J. A. Caggiano, J. A. Clark, C. Deibel, R. Lewis, A. Parikh, P. D. Parker and C. Westerfeldt, Phys. Rev. C **76**, 052802(R) (2007).

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"Pair correlations in nuclei involved in neutrinoless double beta decay: ^{76}Ge and ^{76}Se" S. J. Freeman, J. P. Schiffer, A. C. C. Villari, J. A. Clark, C. Deibel, S. Gros, A. Heinz, D. Hirata, C. L .Jiang, B. P. Kay, A. Parikh, P. D. Parker, J., Qian, K. E. Rehm, X. D. Tang, V. Werner and C. Wrede, Phys. Rev. C **75**, 051301 (2007).

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"Mass measurements of ^{22}Mg and ^{26}Si via (p,t) reactions and Penning traps" J. A. Clark, A. Parikh, F. Buchinger, J. A. Caggiano, J. E. Crawford, C. Deibel, J. P.

Greene, S. Gulick, J. C. Hardy, A. A. Hecht, J. K. P. Lee, A. F. Levand, R. Lewis, B. F. Lundgren, P. D. Parker, G. Savard, N. D. Scielzo, K. S. Sharma, I. Tanihata, W. Trimble, J. C. Wang, Y. Wang, C. Wrede and Z. Zhou, in proceedings of "Nuclei in the Cosmos IX", PoS(NIC-IX) 081 (2006).

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"Is the nuclear spin-orbit interaction changing with neutron excess?" J. P. Schiffer, S. J. Freeman, J. A. Caggiano, C. Deibel, A. Heinz, C.-L. Jiang, R. Lewis, A. Parikh, P. D. Parker, K. E. Rehm, S. Sinha and J. S. Thomas, Phys. Rev. Lett. **92**, 162501 (2004).

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