TRIUMF - EEC SUBMISSION EEC meeting: 201007S *Original Proposal*	**Exp. No.** S1302 - *Active (Stage 2)* **Date Submitted:** 2010-06-29 04:37:16

Title of Experiment:

Precision mass Measurement and half-lives of proton rich In-isotopes

Name of group:

Spokesperson(s) for Group

T. Brunner,   K. Zuber

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

T. Brunner	T.U. Munich	Student (PhD)	40%
K. Zuber	University of Dresden	Professor	30%
M. Simon	TRIUMF	PDF	20%
S. Ettenauer	University of British Columbia	Student (PhD)	10%
J. Dilling	TRIUMF	Research Scientist	10%
A. Gallant	University of British Columbia	Student (PhD)	10%
P.P.J. Delheij	TRIUMF	Research Scientist	5%
V. Simon	MPI-K Heidelberg	Student (Graduate)	5%
A. Lapierre	NSCL	Research Associate	5%
M. Brodeur	NSCL	Research Associate	5%

Beam Shift Requests:

4 shifts on: TITAN
Comment:

We request 4 shifts of beam of the isotopes ^{104}In, ^{105}In and ^{106}In.

14 shifts on: TITAN
Comment:

For the isotopes ^{98}In, ^{99}In and ^{100}In we request beam development with a laser ion source in combination with either a HP Ta or a HP UOx target. The beam requested are 14 shifts as stage 1.

Basic Information:

Date submitted: 2010-06-29 04:37:16

Date experiment ready: 2010-08-01 12:00:00

Summary:

The region of neutron deficient isotopes away from stability is interesting from various perspectives. A rich physics is
associated with proton-rich In nuclides. In the region of A = 100 the neutron deficient region is characterized by the
coexistence of high- and low-spin states leading to reach isomerism whose understanding is important for nuclear structure
physics. Furthermore, it is also an interesting region for nuclear astrophysics as nucleosynthesis via the rp-process has a
path along this region. These two items alone would justify already a detailed investigation of the In-isotopes, however
there are two more physical goals of major importance. The proton rich isotopes have a reasonably long half-life, even ^{100}In
being 13 mass units away from the lightest stable isotope ^{113}In is supposed to live 6.1 s. This supports the hope for a first
measurement on ^{99}In. This isotope is a magic nuclei and the only one of the N=50 isotopes not being characterized at all

yet. Going one beyond the shell closure a measurement of 98In could prove whether magic numbers are still the same in this

region. In addition, a measurement of ^{98}In would be extremely important for fundamental tests of weak interactions and the

determination of the CKM matrix element Vud. The most precise determination of Vud stems from precise measurements

of ft-values from superallowed 0+ to 0+ transitions. However the necessary precision requires to take into account various

correction factors which are extensively discussed in. Especially the hadronic corrections are becoming more and more

apparent for larger A. Thus to determine them more accurately it requires to measure them for heavier nuclides. By now

the heaviest one investigated is ^{74}Rb with a significant error. Thus we propose to go a step beyond to measure ^{98}In,

more than 20 mass units heavier. This will require a half-life measurement in addition to the mass measurement for testing

the magic numbers. The masses of ^{102,104}In have recently been measured still with a relatively large error.

Plain Text Summary: We propose to measure neutron deficient In isotopes reaching from 98In to 106In. This region is interesting from various perspectives. Vud in the CKM matrix can be tested with knowledge of the ft value of 98In. Due to the heavy mass corrections are more sever than in the case of 74Rb. 99In is interesting because it tests the shell model and is the only isotope with a magic shell closure that has never been measured. The isotopes 100In to 106In are of interest for the astrophysical r-p-process. These network calculations heavily depend on the mass.

Summary of Experiment Results:

Primary Beamline: isac2a

ISAC Facilities

ISAC Facility: TITAN

ISAC-I Facility:

ISAC-II Facility:

Secondary Beam

Isotope: 87Rb, 98In, 99In, 100In, 101In, 102In, 103In

Energy: 20

Intensity Requested: 500

Minimum Intensity: 500

Maximum Intensity: 1e7

Energy Units:

Energy spread-maximum:

Time spread-maximum:

Angular Divergence:

Spot Size:

Charge Constraints:

Beam Purity:

Special Characteristics:

Experiment Support

Beam Diagnostics Required:

Tuning will be done on ILE2T:FC3. From there TITAN personal will tune to TITAN.

Signals for Beam Tuning:

Al27

DAQ Support:

All software and hardware required exists.

TRIUMF Support:

ISAC operators to tune the beam from OLIS/ISAC ion source to TITAN.

NSERC:

TITAN is funded by NSERC and NRC.

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TITAN is funded by NSERC and NRC.

Other Funding:

T. Brunner is funded by the Evangelisches Studienwerk Villigst e.V..

Muon Justification:

Safety Issues:

All the isotopes requested are short lived and no contamination is expected.

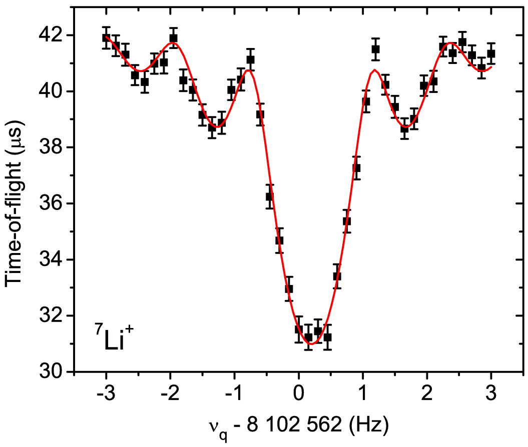
Precision mass Measurement and half-lives of proton rich In-isotopes

July 1, 2010

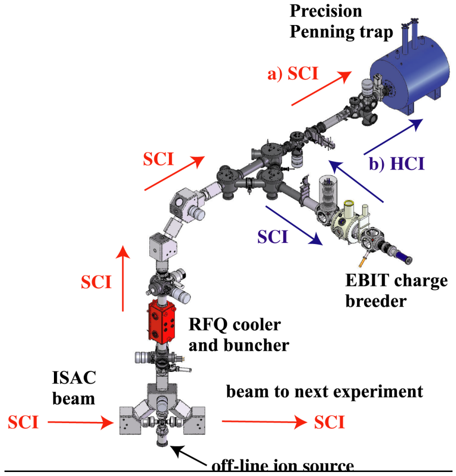
K. Zuber, T. Brunner

1 Scientific goals

The region of neutron deficient isotopes away from stability is interesting from various perspectives. A rich physics is associated with proton-rich In nuclei. In the region of A $\approx$ 100 the neutron deficient region is characterized by the coexistence of high- and low-spin states leading to reach isomerism whose understanding is important for nuclear structure physics. Furthermore, it is also an interesting region for nuclear astrophysics as nucleosynthesis via the rp-process have a path along this region. This two items alone would justify already a detailed investigation of the In-isotopes, however there are two more physical goals of major importance. The proton rich isotopes have a reasonable long half-life, even ^{100}In being 13 mass units away from the lightest stable isotope ^{113}In is supposed to live 6.1 s. The masses of ^{102,104}In have recently been measured still with a relatively large error [1]. This supports the hope for a first measurement on ^{99}In, very close to the proton drip line. This isotope is a magic nuclei (Z=49,N=50) and the only one of the N=50 isotopes not being characterized at all yet. This region of proton rich nuclei could be only tackled recently by producing the heaviest double magic nucleus (Z=N=50) ^{100}Sn [2]. Thus, exploring this region of nuclear shell closure and the verification of magic numbers far away from stability is of great importance. Such nuclei also serve as waiting points in nuclear astrophysics reaction chains and especially the region of ^{99}In and ^{100}Sn thus could have a major impact on the nucleosynthesis via the rp-process [3]. Going one beyond the shell closure a measurement of ^{98}In would clearly show the shell closure. In addition, a measurement of ^{98}In would be extremely important for fundamental tests of weak interactions and the determination of the CKM matrix element V_{ud}. The most precise determination of V_{ud} stems from precise measurements of ft-values from superallowed $0^+ \rightarrow 0^+$ transitions between T=1 analog statues. They uniquely depend on the vector part of the weak interaction and according to the CVC hypothesis and thus the experimental ft-value should be linked to the fundamental vector constant and finally to V_{ud}. However the necessary precision requires to take into account various correction factors which are extensively discussed in [4]. Especially the transition and nucleus-dependent part of radiative corrections depend on the Z of the daughter nucleus, starting vary small but grows smoothly with Z^2. Thus, to determine and investigate them more accurately it requires to measure them for heavier nuclei. By now the heaviest one investigated is ^{74}Rb with a significant error [5, 6]. Thus we propose to go a major step beyond by measuring ^{98}In, an increase in Z by 13. This will require a half-life measurement in addition to the mass measurement for testing the magic numbers. The nuclear structure dependent corrections contributes an uncertainty 3-10 times larger for heavy



(a) Time-of-flight resonance of ^{7}Li$^+$ after an excitation time T_{RF} of 900 ms. Fitted is the theoretical line shape [9].



(b) Experimental setup of TITAN. Ions can be sent from the RFQ either directly to the MPET or to the EBIT for charge breeding.

nuclei like ^{74}Rb than light nuclei because of nuclear-model ambiguities. Thus, an even more dramatic effect can be expected for ^{98}In.

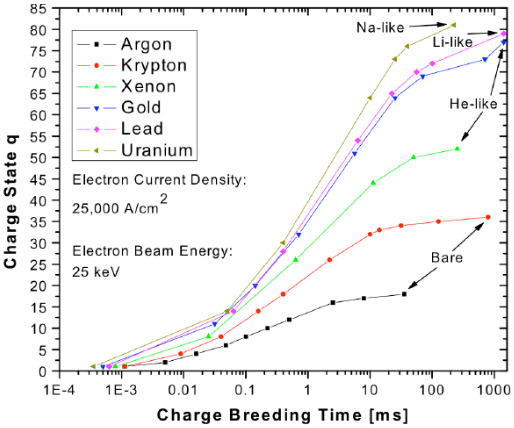
Proton reach indium beams have been successfully created at TRIUMF, ^{103}In could be produced with several hundred ions per second. ISOLDE at CERN cannot produce proton-In isotopes and IGISOL at Jyvaskyla is going for a lengthy shutdown until spring 2011. Thus, there is a unique chance for TITAN to perform this highly exciting measurements.

2 Description of the experiment

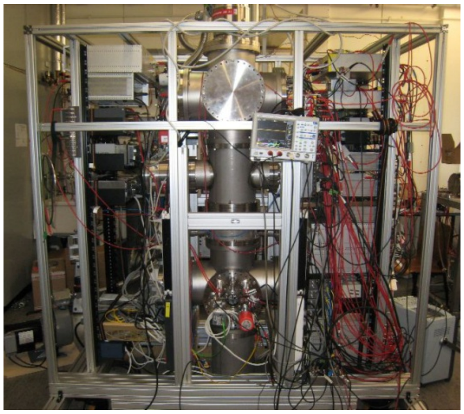
The mass measurement of the proposed In isotopes will be performed at TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN, [7]). TITAN is an experimental setup currently consisting of three ion traps dedicated, but not limited, to high precision mass measurements on short lived radioactive isotopes. Its three ion traps are a radio frequency quadrupole ion cooler and buncher (RFQ), an electron beam ion trap (EBIT) for charge breeding and a Penning trap for high precision mass measurements (MPET). Radioactive ions produced at ISAC are first delivered to TITAN's RFQ where they are decelerated, cooled and bunched. Afterwards, these ion bunches can either be sent directly to the MPET for high precision mass measurements or to the EBIT in order to increase the charge state prior to mass measurements. In the proposed experiment RFQ, EBIT and MPET will be needed. A schematic view of TITAN is shown in Fig. 1b.

The MPET uses the ion cyclotron resonance time-of-flight technique (ICR-TOF)[8, 9] for mass measurements. With this technique ions are captured dynamically in the Penning trap and excited with a radio frequency ν_{RF} for a time T_{RF}. During a measurement T_{RF} is kept constant while ν_{RF} varies around the cyclotron frequency ν_C of the ion of interest. After this excitation the ion is extracted out of the MPET onto a multi channel plate (MCP) and their time-of-flight is recorded. If $\nu_{RF} = \nu_C$ the ions are excited maximal and their time-of-flight is minimal. A measured time-of-flight resonance of ^{7}Li$^+$ is shown in Fig. 1a. With stable ^{7}Li$^+$ from an off-line surface ion source a precision of $4 \cdot 10^{-9}$ was achieved [10].

The relative precision of this method is constrained by $\frac{\delta m}{m} \propto \frac{1}{q\,B\,T_{RF}\sqrt{N}}$. For a given T_{RF} and B the precision scales linearly with the charge state q and N^2. By increasing the charge state q the



(a) Charge breeding time for different elements [12].



(b) Picture of the Giessen MR-TOF-MS. The device is about 2 m x 2 m x 1 m in dimensions.

precision of a mass measurement can be increased. In order to increase the charge state ions can be sent to TITAN's EBIT. During a first on-line experiment with ^{44}K^{4+} the EBIT was successfully commissioned and has been operational since then [11].

Mass measurements with a Penning trap use the correlation $\nu_C = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$ between cyclotron frequency ν_C and mass-to-charge ratio m/q in a magnetic field B. From a known charge state and magnetic field strength ($B\,[MPET] = 3.7\,\mathrm{T}$) the mass can be deduced by determining the cyclotron frequency ν_C. To determine B precisely, a calibration measurement is performed with a well known mass. Based on the mass of the calibrant m_2, the mass of the ion of interest m_1 is deduced from the frequency ratio of both measurements $m_1 = \frac{q_1}{q_2} \cdot \frac{\nu_2}{\nu_1} \cdot m_2$. In order to limit the uncertainty contribution of the calibrant a well known mass needs to be chosen.

In the mass region $A \cong 100$ the most precisely known masses have uncertainties of 2 keV. The anticipated precision for ^{99}In in this proposal is less than 1 keV. Therefore, we propose a two stage measurement. In a first stage the masses of ^{104}In^{13+}, ^{105}In^{13+} and ^{106}In^{13+} will be measured versus the calibrant ^{87}Rb^{11+}. In13+ is in the electron configuration of Kr and can thus be charge bred to this electron shell configuration very efficiently. The mass of ^{87}Rb is very well known with an uncertainty of 12 eV [13]. The difference in charge-to-mass ratio between the In isotopes and the calibrant Rb add an uncertainty of $1 \cdot 10^{-9}$ to the measurement. The expected uncertainty for the measurement of ^{104}In to ^{106}In is 100 keV. For this first stage we request ^{87}Rb from OLIS. The required charge breeding time to produce a 13+ ion is less than 0.5 ms (Fig. 1a) and is not limited by the half lives listed in Table 1.

In a second stage the masses of singly charged ^{98}In to ^{103}In will be measured using ^{104}In1+ as the calibrant. Charge breeding is not feasible due to the low production yields. The precision aimed at is in the sub-keV region and can be achieved with the previously measured ^{104}In1+ as the calibrant.

Proton rich Indium isotopes have been produced at ISAC with a Tantalum target in combination with a surface ion source. During an earlier experiment with Indium at TITAN, ^{107}In was sent to an open access Penning trap for in-trap-decay spectroscopy. During this measurement the electron capture branching ratio of ^{107}In to ^{107}Cd has been measured [14]. In the x-ray spectra no significant contamination with ^{107}Cd has been found. ^{107}Sn could not be detected with the x-ray detectors because it does not decay by electron capture. For the proposed measurement little contamination is expected.

Contaminants that are about 100 times less abundant that the isotope of interest can easily be cleaned in the Penning trap prior to the mass measurement at the cost of measurement time. The

Isotope	Half live [s]	M.E. [keV]
^{98}In	0.045(0.023)[13]	53900(200)*
^{99}In	3.1(0.8)[13]	61270(400)*
^{100}In	5.9(.2)	64170(250)
^{101}In	15.1(.3)	68610(300)*
^{102}In	23.3(.1)	70690.4(54)[20]
^{103}In	60(1)	74599(25)
^{104}In	15.7(.5)	76176.5(51)[20]
^{105}In	304.2(4.2)	79481(17)
^{106}In	312(6)	80606(12)

Table 1: Mass excess [13] and half live (NNDC) of the proposed In isotopes. Values marked with (*) are extrapolated. The half lifes of ^{98}In ^{99}In are from [13].

isotopes of interest listed in Table 1 are longlived enough that dipole cleaning can be performed in the MPET. The only exception is ^{98}In. In this case a time-of-flight mass separation can be used.

In winter 2010/2011 a multi-reflection time-of-flight mass-spectrometer (MR-TOF-MS) will be installed at TITAN right after the RFQ. THE MR-TOF-MS was developed at the University of Giessen, Germany. Ions are injected into the device and are reflected back and forth between two electrostatic mirrors. Due to their difference in mass different isobars spread in time and can be separated. After a traveling time of 10 ms a mass resolution of $R \approx 7000$ could experimentally be demonstrated [15]. Longer travel times result in higher resolution. If the In beam is significantly contaminated, this device can be used to produce isobarically pure samples.

3 Experimental setup

The TITAN facility is completely set up and has successfully performed high precision mass measurements on short lived radioactive nuclei (^{8}He [16], ^{11}Li [17] and ^{11,12}Be [18, 19]). All necessary equipment exists.

4 Readiness

The TITAN facility is fully commissioned and operates on a daily basis. In order to optimize the system a minimum of ∼1 week notice is required. Data acquisition and the software tools to analyze the data exist and are used on a daily basis.

5 Beam time required

The isotopes requested are listed in Table 2. Their half lives range from ∼ 1 s up to ∼6 min so they are long lived enough to perform the proposed measurements but do not build up contamination in the system. One exception is ^{98}In with a half life of 45 ms. This half life is well within the reach of TITAN's experimental limits (shortest lived isotope measured at TITAN: ^{11}Li, $t_{1/2} < 9$ ms [17]).

Current mass excess values and uncertainties of the proposed isotopes are listed in Table 1[13, 20]. In most cases the uncertainty is larger than 80 keV and in the cases of ^{98}In, ^{99}In and ^{101}In the mass excess is based on extrapolations. In order to test theoretical models an uncertainty of less than 1 keV

Isotope	Target	ISAC yield [s^{-1}]	Requested shifts	Stage
^{98}In	Ta HP		5	1
^{99}In	Ta HP		4.5	1
^{100}In	Ta HP		4.5	1
^{101}In	Ta HP			1
^{102}In	Ta HP			1
^{103}In	Ta HP	1.00e+2 (Ta)		1
^{104}In	Ta	1.20e+3	0.5	2
^{105}In	Ta	3.20e+4	0.5	2
^{106}In	Ta	1.60e+5	0.5	2

Table 2: Requested beam time.

is required. Mass measurements with charge-bred ions in a Penning trap can achieve this precision and additionally produce not only precise results but also accurate ones.

The overall efficiency of TITAN for mass measurements on singly charged ions is measured to be 0.2%. The charge breeding efficiency is expected to be 10%. Generally, measurements are performed with only one particle in the trap in order to exclude Coulomb disturbtions with other ions. With a beam of more than 500 paricles/s in the mass region of $A \cong 100$ and an excitation time $T_{RF} = 1\,\mathrm{s}$ an uncertainty of 2 keV is achieved after 6 hrs of data taking. In the same time a precision of ~0.2 keV is achievable with In^{13+} and Rb^{11+} as calibrant. Within 4 shifts (3 x 6 hrs measurement plus 6 hrs overhead) the precision of ^{104}In to ^{106}In can be determined to ~0.2 keV. This measurement requires ^{87}Rb from OLIS during the experiment to perform calibration measurements on a regular base. The isotopes ^{104}In to ^{106}In have been observed at ISAC's yield station. Therefore, we request stage 2 for these isotopes.

Measuring the masses of ^{98}In to ^{103}In is feasible at TITAN if a yield of $\sim 5 \cdot 10^2$ particles/s can be delivered. It was shown in the past (^{8}He, [16]) that if an isotope can be identified in the yield station, the yield is large enough to perform mass measurements with TITAN. We therefore request these isotopes as stage 1 and request beam development for them. If this yield can be delivered to TITAN the masses of ^{99}In and ^{100}In can be measured to a precision below 1 keV after 4.5 shifts for each isotope. Therefore, we request 9 shifts for the mass measurement of these two isotopes and another 5 shifts for ^{98}In. This measurement will provide an essential input for the determination of V_{ud} in the CKM matrix.

The yields of a Ta target in combination with a surface ion source are sufficient to achieve the precision desired. The use of a laser ion source drastically increases the ionization efficiency. At ISOLDE a total ionization efficiency for In isotopes of 7% could be measured [21]. A laser ionisation ion source would also help to produce an isobarically pure In beam.

Since the yield for neutron deficient Indium lighter than A=103 has not been verified at TRIUMF, we request beam development with a high power Ta target in combination with a laser ionization source to measure the isotopes ^{98}In to ^{103}In.

6 Data analysis

The TITAN facility has all the necessary data analysis softwares and computers.

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Publications – Thomas Brunner

In-trap decay spectroscopy for $2\nu\beta\beta$ decay experiments
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First Online Operation of the TITAN EBIT
NIM A, in preparation
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Collinear laser spectroscopy with reverse-extracted bunched beams at TRIUMF
Hyperfine Interactions, submitted
E. Man´e, J. A. Behr, J. Billowes, T. Brunner, M. Brodeur, F. Buchinger, J.E. Crawford, J. Dilling, S. Ettenauer, C.D.P. Levy, A. Voss and M. R. Pearson

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A.T. Gallant, M. Brodeur, T. Brunner, S. Ettenauer, A. Lapierre, R. Ringle, V. Simon, P. Delheij, and J. Dilling for the TITAN collaboration

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T. Brunner for the TITAN-EC collaboration

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