TRIUMF - EEC SUBMISSION EEC meeting: 201012S *Progress Report*	TRIUMF	**Exp. No.** S1321 - *Active (Stage 2)* **Date Submitted:** 2010-11-22 09:24:30

Title of Experiment:

Mass measurements for double beta decay experiments

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)	20%
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J. Dilling	TRIUMF	Research Scientist	10%
R. Ringle	NSCL	Research Scientist	5%
A. Lapierre	NSCL	Research Associate	5%

Beam Shift Requests:

6 shifts on: ILE2T

Comment:

The requested beam time depends if the proposed bb decay pairs can be measured simultaneously.

Beam Shifts Used:

Beam Shifts Remaining:

Basic Information:

Date submitted: 2010-11-22 09:24:30

Date experiment ready: 2010-12-15 12:00:00

Summary:

The search for neutrino less double beta decay ($0\nu\beta\beta$) is one of the frontiers in nowadays physics. This decay is forbidden in the Standard Model as two nucleons decay simultaneously without the emission of neutrinos. If this decay is observed, lepton number conservation would be violated and the neutrino has to be a Majorana particle, i.e. neutrino and anti-neutrino are identical.

Worldwide, several experiments, such as GERDA, MAJORANA, COBRA, CUORECINO, NEMO, SNO$^+$, and others, aim to investigate this rare decay. However, the Standard Model allowed process $2\nu\beta\beta$ has already been observed with half lives larger than $\sim 10^{19}$ years. A list of $\beta\beta$ isotopes that are presently of experimental interest is presented in along with the most recent $2\nu\beta\beta$ half life measurements.

If a $0\nu\beta\beta$ decay occurs, both electrons will share the total energy available from the decay, i.e. in the case of $\beta^-\beta^-$ the summed electron energy is equal to the Q-value. Therefore, accurate knowledge of the Q-value provides important information for simulations and the design of $\beta\beta$ decay experiments as well as for the analysis of the recorded decay spectra. High precision mass measurements can provide this knowledge by measuring the atomic masses of mother and daughter isotope. In recent years, these

measurements have been performed for several $\beta\beta$ decay pairs such as ^{76}Ge$\rightarrow^{76}$Se, ^{100}Mo$\rightarrow^{100}$Ru, and ^{150}Nd$\rightarrow^{150}$Sm. However, the Q values of the $\beta \beta$ decay candidates ^{48}Ca$\rightarrow^{48}$Ti and ^{124}Sn$ \rightarrow^{124}$Te are only known with an uncertainty of 4\,keV and 2\,keV, respectively. In ^{48}Ca conventional β decay is suppressed due to spin selection rules. The high Q value of this decay leads to an increased phase space factor and thus to an increase in the decay rate. Currently, the CANDELS experiment is being designed that will investigate the $\beta\beta$ decay of ^{48}Ca. The Penning trap mass measurement of ^{48}Ca and ^{48}Ti would dramatically decrease the uncertainty on the Q value and provide valuable input for the design of the detector. It is noted here, that the isotope abundance of ^{48}Ca is 0.2\% and as a consequence, ^{48}Ca is only of minor interest in the search of $0\nu\beta\beta$ decay. The isotope ^{124}Sn has been investigated as a possible candidate for $\beta\beta$ decay. So far, an upper limit of the $2\nu\beta\beta$ decay has been reported but no large scale experiment is currently considering its use. However, it is important to determine the Q value to provide experimental input for future development of $\beta\beta$ decay experiments.

Furthermore, we propose to measure the Q values of the pairs ^{112}Sn$\rightarrow^{112}$Cd, and ^{150}Nd$\rightarrow^{150}$Sm to verify previous measurements. Especially in the case of ^{112}Sn$ \rightarrow^{112}$Cd it is important to determine the Q value because currently, the existence of a so-called resonance is excluded. This has to be verified.

Plain Text Summary: We propose to measure the Q values of the $\beta\beta$ decay pairs ^{48}Ca$\rightarrow^{48}$Ti, ^{124}Sn$\rightarrow^{124}$Te, ^{112}Sn$ \rightarrow^{112}$Cd, and ^{150}Nd$\rightarrow^{150}$Sm. The Q values of the first two decays listed are known with uncertainties of less than 2keV. The aim of this proposal is to determine the Q value with an uncertainty of 200eV, that is an improvement of one order of magnitude. In the last two cases we propose to measure the Q value to verify previous mass measurements.

Summary of Experiment Results:

Primary Beamline:

ISAC Facilities

ISAC Facility: TITAN

ISAC-I Facility:

ISAC-II Facility:

Secondary Beam

Isotope: 48Ca, 48Ti, 112Sn, 112Cd, 124Sn, 124Te, 150Nd

Energy: 20

Intensity Requested: 5000+

Minimum Intensity: 500

Maximum Intensity:

Energy Units: keV

Energy spread-maximum:

Time spread-maximum:

Angular Divergence:

Spot Size:

Charge Constraints:

Beam Purity: 0.5-1%

Special Characteristics:

Experiment Support

Beam Diagnostics Required:

All diagnostic tools are already installed in the beam line. The beam is delivered to ILE2T:FC3 by ISAC ops. From there, the beam is tuned by members of the TITAN group.

Signals for Beam Tuning:

ILE2T:FC3

DAQ Support:

All DAQ is installed and operational.

TRIUMF Support:

The OLIS beam has to be developed. The sources are commercially available. Small amounts of 48Ca can be obtained from the Technical University Munich.

NSERC:

TITAN is funded by NSERC. No additional investments are required.

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Other Funding:

Muon Justification:

Safety Issues:

No special safety hazards are present.

Precision mass measurements for $\beta\beta$ decays

December 1, 2010

T. Brunner, K. Zuber

1 Scientific goals

The search for neutrino less double beta decay ($0\nu\beta\beta$) is one of the frontiers in nowadays physics. This decay is forbidden in the Standard Model as two nucleons decay simultaneously without the emission of neutrinos. If this decay is observed, lepton number conservation would be violated and the neutrino has to be a Majorana particle, i.e. neutrino and anti-neutrino are identical.

Worldwide, several experiments, such as GERDA, MAJORANA, COBRA, CUORECINO, NEMO, SNO^+, and others, aim to investigate this rare decay. However, the Standard Model allowed process $2\nu\beta\beta$ has already been observed with half lives larger than $\sim 10^{19}$ years. A list of $\beta\beta$ isotopes that are presently of experimental interest is presented in [1] along with the most recent $2\nu\beta\beta$ half life measurements.

If a $0\nu\beta\beta$ decay occurs, both electrons will share the total energy available from the decay, i.e. in the case of $\beta^-\beta^-$ the summed electron energy is equal to the Q-value. Therefore, accurate knowledge of the Q-value provides important information for simulations and the design of $\beta\beta$ decay experiments as well as for the analysis of the recorded decay spectra. High precision mass measurements can provide this knowledge by measuring the atomic masses of mother and daughter isotope. In recent years, these measurements have been performed for several $\beta\beta$ decay pairs such as ^{76}Ge$\rightarrow^{76}$Se [2], ^{100}Mo$\rightarrow^{100}$Ru [2], and ^{150}Nd$\rightarrow^{150}$Sm [3]. However, the Q values of the $\beta\beta$ decay candidates ^{48}Ca$\rightarrow^{48}$Ti and ^{124}Sn$\rightarrow^{124}$Te are only known with an uncertainty of 4 keV and 2 keV, respectively [4]. In ^{48}Ca conventional β decay is suppressed due to spin selection rules. The high Q value of this decay leads to an increased phase space factor and thus to an increase in the decay rate. Currently, the CANDELS experiment [5, 6] is being designed that will investigate the $\beta\beta$ decay of ^{48}Ca. The Penning trap mass measurement of ^{48}Ca and ^{48}Ti would dramatically decrease the uncertainty on the Q value and provide valuable input for the design of the detector. It is noted here, that the isotope abundance of ^{48}Ca is 0.2%.

The isotope ^{124}Sn has been investigated as a possible candidate for $\beta\beta$ decay. So far, an upper limit of the $2\nu\beta\beta$ decay has been reported [7] but no large scale experiment is currently considering its use. However, it is important to determine the Q value to provide experimental input for future development of $\beta\beta$ decay experiments.

At SNO^+, located at the Sudbury underground laboratory, the $\beta\beta$ decay of ^{150}Nd will be investigated [8]. Recently, the Q value of the decay ^{150}Nd$\rightarrow^{150}$Sm has been measured at the JYFLTRAP Penning trap mass spectrometer to be 3371.38(20) keV [3]. However, in the case of ^{130}Te$\rightarrow^{130}$Xe the Q value of the decay was measured by several groups using a Penning trap technique but the determined values varied by 1.5 sigma. The measured value of $Q_{\beta\beta}(^{130}\text{Te}) = 2527.518(13)\,\text{keV}$ [9]

	Q value [keV]	Uncertainty [keV]	
$^{48}Ca \rightarrow ^{48}Ti$	4274	4	[4]
$^{124}Sn \rightarrow ^{124}Te$	2287.7	2.1	[4]
$^{112}Sn \rightarrow ^{112}Cd$	1919.82	0.16	[15]
$^{150}Nd \rightarrow ^{150}Sm$	3371.38	0.20	[3]

Table 1: Summary of proposed isotopes.

does not agree with $Q_{\beta\beta}(^{130}Te) = 2527.01(32)$ keV [10]. Therefore, we propose to re-measure the Q value of $^{150}Nd \rightarrow ^{150}Sm$ to verify the previous measurement.

The main experimental focus of $\beta\beta$ decay experiments lies on the detection of the $\beta^-\beta^-$ process. Nevertheless, $\beta^+\beta^+$ offers an alternative possibility to test the Standard Model and investigate the nature of the neutrino [11]. $\beta^+\beta^+$ is accompanied by two other processes, double electron capture ECEC and β^+EC. In the process of $\beta^+\beta^+$ the available energy is reduced by $4\,m_ec^2$ because two positrons need to be created. Therefore, these rates are reduced by typically three to four orders of magnitude compared to $\beta^-\beta^-$ decays. In Ref. [12] it was first mentioned that in the case of 0νECEC a resonance condition could exist. In such a resonance condition an energy level exists in the decay product that has an energy close to the $Q_{\beta\beta}$ value. The presence of this condition would then enhance the transition rate by up to six orders of magnitude [13]. To determine whether a resonance condition can exist, the energy of the excited state as well as the Q value need to be known precisely.

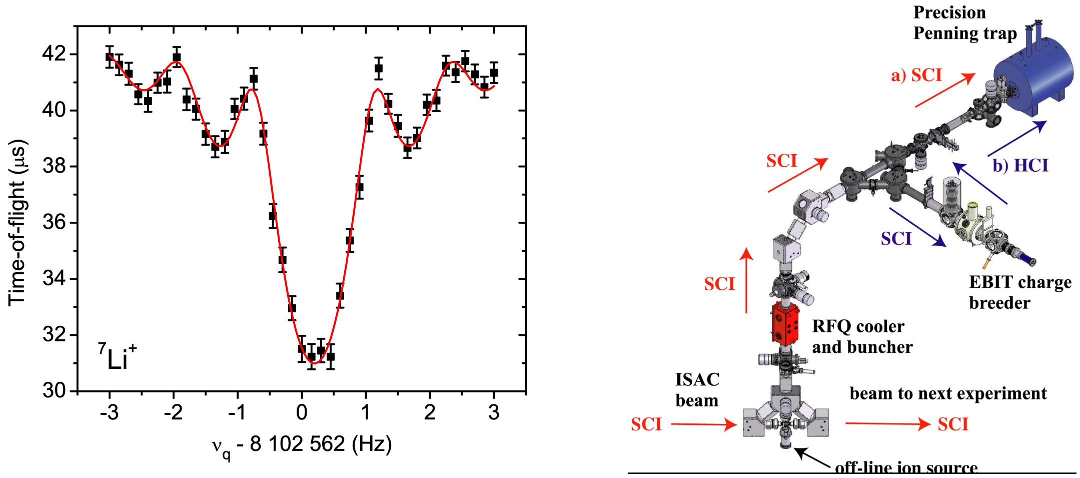
In the decay of $^{112}Cd \rightarrow ^{112}Cd$ this resonance condition was proposed, but recent measurements of the excited state at TRIUMF [14] and of the Q value at JYFLTRAP [15] showed that this condition is energetically not present. To confirm this mass measurement and exclude a resonance we propose to remeasure the Q value of the $\beta\beta$ decay mother isotope ^{112}Cd.

In summary, we propose to measure the Q values in $\beta\beta$ decays listed in Table 1 by measuring the masses of mother and daughter isotope using the TITAN mass measurement Penning trap. The mass measurement of the doublets $^{48}Ca \rightarrow ^{48}Ti$ and $^{124}Sn \rightarrow ^{124}Te$ are of great scientific interest because they directly influence the design of $\beta\beta$ decay experiments. With the measurement of the doublets $^{150}Nd \rightarrow ^{150}Sm$ and $^{112}Sn \rightarrow ^{112}Cd$ we propose to confirm previous measurements. These measurements are important for the design of SNO++ and to exclude the resonance condition in the latter doublet. In these measurements we aim at an uncertainty of 0.2 keV.

2 Description of the experiment

The mass measurement of the proposed isotopes will be performed at TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN, [16]). TITAN is an experimental setup currently consisting of three ion traps dedicated, but not limited, to high precision mass measurements on short lived radioactive or stable 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 or stable isotopes from OLIS 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)[17, 18] for mass measurements. With this technique ions are captured dynamically in the Penning trap and excited



(a) Time-of-flight resonance of ^{7}Li$^+$ after an excitation time T_{RF} of 900 ms. Fitted is the theoretical line shape [18].

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

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 [19].

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 precision of a mass measurement can be increased. At TITAN, the ion's charge state is increased in the EBIT. During a first on-line experiment with ^{44}K^{4+} the EBIT was successfully commissioned and has been operational since then [20]. Recently, radioactive ^{74}Rb^{8+} has been successfully measured with the TITAN setup.

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 order to determine the Q value precisely, only the frequency ratio between mother and daughter isotope is required with high accuracy and no other calibrant is required.

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 isotopes of interest are stable so that dipole cleaning can be performed in the MPET. The only difficulty is ^{48}Ca with an abundance of 0.2% but enriched source material is available from the Technical University in Munich.

Isotope	Charge state	Requested time [hrs]	Stage
^{48}Ca	1^+ or 9^+	9+2	2
^{48}Ti	1^+ or 9^+	9+2	2
^{124}Sn	14^+	6+2	2
^{124}Te	14^+	6+2	2
^{112}Sn	14^+	6+2	2
^{112}Cd	14^+	6+2	2
^{150}Nd	23^+	3+2	2
^{150}Sm	23^+	3+2	2

Table 2: Requested isotopes and requested beam time.

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 [21], ^{11}Li [22], ^{44}K^{4+} [20], and ^{11,12}Be [23, 24]). 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 1. They are all stable and can be produced with OLIS. This Table also lists the Q values and their uncertainties. The aim of this proposal is to measure the Q values with an uncertainty of 200 eV. Beam intensities are no issue because the beam is delivered from OLIS. However, the requested beams have not been produced at OLIS so far and need to be developed.

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 disturbances with other ions. With a beam of more than 5000 particles/s in the mass region of $A \cong 50$ and an excitation time $T_{RF} = 1\,\mathrm{s}$ an uncertainty of 0.2 keV with singly charged ions is achieved after 9 hrs of data taking. ^{48}Ca will be measured singly charged or in the charge state 9^+ depending on the isotope abundance of the enriched material. The same precision of ∼0.2 keV is achievable with ^{150}Nd^{23+} and ^{150}Sm^{23+} after 3 hrs. In the case of Sn^{14+} an uncertainty of ∼0.2 keV is reached after bout 6 hrs of beam time. The isotopes and the requested beam time are listed in Table 2. For each isotope and overhead of 2 hrs is estimated if they are delivered separately. This overhead is reduced if the isotopes are measured in groups. Ideally, mother and daughter isotope are measured simultaneously. If this is not possible, the Q value is determined by measuring the isotope of interest with a calibrant. All quoted times assume the use of an calibrant. They reduce by a factor of two if mother and daughter are measured simultaneously.

The measurement of $\beta\beta$ decay Q values provides important information for the design and the data analysis of $\beta\beta$ decay experiments. The high precision Penning trap at TITAN allows these measurements. Within a short time, the Q values of previous measurements can be improved and in the cases of $^{48}Ca \rightarrow ^{48}Ti$ and $^{124}Sn \rightarrow ^{124}Te$ the current uncertainty can be improved by at least one order of magnitude.

6 Data analysis

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

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