TRIUMF - EEC SUBMISSION EEC meeting: 200807S *Original Proposal*	TRIUMF	**Exp. No.** S1170 - *Pending (Stage 1)* **Date Submitted:** 2008-06-09 09:05:50

Title of Experiment:

Mass of ^{32}Si and the Isobaric Multiplet Mass Equation

Name of group:

Spokesperson(s) for Group

S. Triambak, J. Dilling

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

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Beam Shift Requests:

12 shifts on: TITAN

Basic Information:

Date submitted: 2008-06-09 09:05:50

Date experiment ready: 2008-08-18 12:00:00

Summary:

We propose to measure the ^{32}Si mass with high-accuracy and precision using the TITAN Penning trap. The isotope will be produced from the β decay of ^{32}Al using EBIT which will be operated in Penning trap mode. After purification and cooling using buffer-gas collisions, the daughter ^{32}Si ions will be sent to the measument Penning trap (TITAN) for the mass measurment.

Our results will resolve important issues regarding the Isobaric Mulitplet Mass equation for the A =32, T=2 quintet. These results will also be useful for future calculations of isospin mixing for the T = 2 superallowed emitter ^{32}Ar, a particular case where the isospin breaking corrections are rather large. The experimentally obtained corrections from another experiment will then be compared to the calculated values to place CKM unitarity and CVC tests on a secure footing.

Plain Text Summary: We plan to measure the mass of the long-lived isotope 32Si which will be produced via the beta-decay of its short-lived parent 32Al. A high-precision mass measurement of the 32Si will illuminate our understanding of charge-dependent interactions within the atomic nucleus and provide useful information about theoretical

predictions in particular nuclei that are used as probes for new physics, beyond the Standard Model.

Summary of Experiment Results:

Primary Beamline: isac2a

ISAC Facilities

ISAC Facility: TITAN

ISAC-I Facility:

ISAC-II Facility:

Secondary Beam

Isotope: 32Al

Energy: low

Intensity Requested: 700

Minimum Intensity: 300

Maximum Intensity: 10000

Energy Units:

Energy spread-maximum:

Time spread-maximum:

Angular Divergence:

Spot Size:

Charge Constraints:

Beam Purity:

Special Characteristics:

Experiment Support

Beam Diagnostics Required:

Signals for Beam Tuning:

DAQ Support:

TRIUMF Support:

NSERC:

NSERC:

Other Funding:

Muon Justification:

Safety Issues: Safety issues for TITAN experiments have already been addressed before and have met approval.

The EEC committees strongly recommend that you limit your submissions, including figures and tables, to no more than 4 pages for the MMSEEC or 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, including 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.

We propose a measurement of the ^{32}Si mass with an uncertainty of $\delta M/M = 10^{-9}$ using the TITAN Penning trap at TRIUMF. This experiment is part of a series of high-precision measurements in the $A = 32,\ T = 2$ quintet that provide stringent tests of theoretical models and the approximations therein. The following section describes the motivation for this measurement, in particular to test the isobaric multiplet mass equation (IMME) for this multiplet and obtain information to extract isospin mixing corrections theoretically. These corrections can then be compared to experimental values. Such comparisons place CKM unitarity tests on a secure footing.

1 Scientific justification:

1.1 Background

The first penning trap mass measurement in the multiplet was performed at ISOLDE where the mass of ^{32}Ar was determined with a relative uncertainty of 6×10^{-8} [1]. This was motivated by a previous determination of the $\beta-\nu$ angular correlation in the $0^+ \rightarrow 0^+$ β decay of ^{32}Ar via a detailed analysis of the shape of the delayed proton group following the superallowed decay [2]. The recoiling daughter nucleus causes broadening of the delayed proton peak, which imparts the $\beta-\nu$ correlation information that is used to set bounds on scalar couplings to the weak interaction. It was thereby important to obtain the Q_{EC} value of the decay with sufficient precision.
Furthermore, a recent determination of the superallowed branch in ^{32}Ar β decay [3] completes the first high-precision ft value measurement for a $T = 2$ superallowed emitter. The measured ft value is used to experimentally determine the isospin-symmetry-breaking correction for the superallowed decay of ^{32}Ar. This measurement provides a stringent test of the theoretical calculation of isospin symmetry breaking, which in this particular nucleus, $\delta_C = 2.0(4)\%$ [4], is significantly larger than any of the nine 'classic' $T = 1$ cases (used for CVC and CKM unitarity tests) that share the same model space. The correction comprises of 'radial overlap' and 'isospin mixing' components, which are calculated to be $\delta_C^{\mathrm{ro}} = 1.4\%$ and $\delta_C^{\mathrm{im}} = 0.6\%$ [4]. The measurement of Ref. [3] yields an experimental

value of $\delta_C^{\mathrm{exp}} = 2.4(8)\%$, in agreement with the predictions. A more meaningful comparison to the theory can be achieved by separating the two contributions to the correction. Preliminary analysis of data from the experiment in Ref. [2] shows indications of isospin mixing with a state ≈ 250 keV above the isobaric analog state that has the $\beta - \nu$ correlation corresponding to a Fermi transition [5]. A thorough analysis of the data will provide an accurate measurement of δ_C^{im} experimentally.

1.2 The IMME and its relevance

The approximate charge independence of the strong interaction implies that the nucleon wavefunction is invariant under rotations in isospin space. Such isospin symmetry implies that the members of an isobaric multiplet are $2T + 1$-fold degenerate and must have identical masses. This degeneracy is broken by the electromagnetic interaction, which can be described using two-body forces. The two-body charge-dependent interaction can be written at tree-level as the sum of an isoscalar, isovector and an isotensor operator of rank 2, such that the masses of the members of an isobaric multiplet are related to the first-order as $M(T_z) = a + bT_z + cT_z{}^2$, where $T_z = (N - Z)/2$. This is known as the isobaric multiplet mass equation (IMME)[6, 7].

In the past many experimental tests have been carried out looking for potential deviations from the IMME [8]. These tests have shown remarkable agreement with the model, the only two significant deviations found in light nuclei ($A < 10$) with unbound states [9]. A recent measurement of the ^{35}K mass at ISOLDE indicated the requirement of a large cubic term to fit the $A = 35,\ T = 3/2$ quartet. However, many additional measurements are still required to identify the possible causes for such a breakdown [10].

This reasonable success has made the IMME a useful tool to predict masses away from the valley of stability when direct measurements are difficult. Such predictions have been used to map the proton drip line over a wide range, determine the *rp*-process path in stellar nucleosynthesis and identify candidates for diproton emission [11]. In addition, for shell-model calculations of δ_C^{im} corrections mentioned previously, the charge-dependent interaction is adjusted so that the coefficients of the IMME for the multiplet were reproduced. This strategy was used to reduce the model dependence in the calculation of δ_C^{im} [12].

The experimental determination of δ_C^{im} for ^{32}Ar provides strong motivation to revisit the IMME for the $A = 32,\ T = 2$ quintet, which is the most precisely measured quintet to date. A recent high-precision measurement of the excitation energy of the lowest $T = 2$ state in ^{32}S using the $^{31}\mathrm{P}(p, \gamma)$ reaction obtained the excitation energy to be 12047.96(28) keV [13], $\approx 7\sigma$ higher than the previously measured value of 12045.0(4) keV [14]. This resulted in significant disagreement with the IMME prediction. Reasonable agreement could be achieved using a small cubic term, $dT_z{}^3 = 0.54 \pm 0.16$ keV, which, if accepted at face value, would be the most precisely determined violation of the IMME. It is possible that this violation could be due to isospin-mixing with either of two $T = 0$ levels below the $T = 2$ state in ^{32}S. However, the experiment in Ref. [13] observed no evidence for such mixing, although the mixing scenario can still not be ruled out.

Another possible reason for the apparent breakdown of the IMME could be an erroneous mass measurement. At the moment the ^{32}Si mass seems to be the 'weakest link' in the multiplet. In the latest atomic mass compilation [15], the ^{32}Si mass is extracted from the $^{31}\mathrm{S}(n, \gamma)$ γ-ray energy published in Ref. [16]. The unreasonably small published uncertainty of 0.0005 keV in the mass was inflated by the authors of [15] to 0.05 keV by studying how well other known γ-ray energies were reproduced. In a later publication, the authors of Ref. [16] themselves presented a revised evaluation of the ^{32}Si mass with a quoted uncertainty of 0.822 μu or 0.77 keV without any details of the systematic effects affecting their measurement [17]. Either scenario leads to a significant violation of the IMME. Furthermore, if the data set were fit to the IMME using the remaining four members of the multiplet, there is excellent agreement with the model (with $Q(\chi^2, \nu) = 0.50$), which provides added motivation to remeasure the ^{32}Si mass.

In summary, an improved measurement of the ^{32}Si mass using TITAN is an important step to resolve this outstanding issue and improve on what is already the most stringent test of the IMME. This will provide useful information on the efficacy of the model to predict masses and level energies in the absence of experimental data. The revised IMME coefficients will play an important role in future calculations of δ_C^{im} for ^{32}Ar superallowed decay.

2 Experimental method

The long-lived ^{32}Si ($t_{1/2} \approx 150$ yr) can be produced at TRIUMF via the β^- decay of its short-lived parent ^{32}Al ($t_{1/2} = 33(4)$ ms). The daughter ^{32}Si will then be transported to the TITAN precision Penning trap for the mass measurement. This can be done using two methods:

1. Offline measurement: The required number of ^{32}Al ions are first implanted into a metal foil. The foil is then heated (after the short lived radioactivity from ^{32}Al and other contaminants have decayed away) to make Si vapor, which can be ionized with an ECR ion-source to produce a highly pure ^{32}Si beam which can directly sent to the measurement Penning trap.

2. Online measurement: The ^{32}Si can be produced by in-trap-decay of ^{32}Al ions. In such a process, the radioactive ion-beam of the parent nuclide is first decelerated, cooled and bunched in a linear RF trap. These ions are then transferred to a preparation Penning trap (EBIT), which has a relatively deep potential (some kV) well so that a fair fraction of the recoiling daughter nuclides are captured. The EBIT will be operated in Penning trap mode, hence without the electron beam, and will be ideally suited to recapture the recoiling ions, once filled with buffer gas. The Si-ions will be stored in this trap for a some time, and further cooled and purified of isobaric contaminants by mass selective buffer gas cooling. Finally, the ^{32}Si ions will be sent to the measurement Penning trap (TITAN) for the mass measurement.

We opted for the latter option due to a number of reasons. Preliminary estimates [18] show that with ≈ 50 μA of 500 MeV protons incident on a Ta target and the use of the TRILIS laser ion-source, the ^{32}Al yield will be ≈ 500 s^{-1}. This would not be conducive for the offline experiment because of the long implantation time required for a proper measurement. In addition, the offline method will also be limited by the low extraction and ionization efficiency of ^{32}Si and potential impurities from O_2 molecules. On the other hand, the in-trap-decay method will not be constrained by the low yield of the radioactive beam and will be relatively free of isobaric contaminants. It will also allow a precision measurement of the neutron-rich ^{32}Al as well, which will be a useful byproduct of this work. In the next section we explain the experimental aspects in greater detail.

3 Experimental details

By now, Penning trap mass measurement at TITAN can be routinely performed on isotopes with half-lives as short as 10 ms. This is done by having the ions directly delivered from the ISAC ion source to TITAN. Here, we propose an additional step of bringing a beam of the mother-nuclei into TITAN. This procedure bypasses the difficulty in producing and delivering a Si-beam.

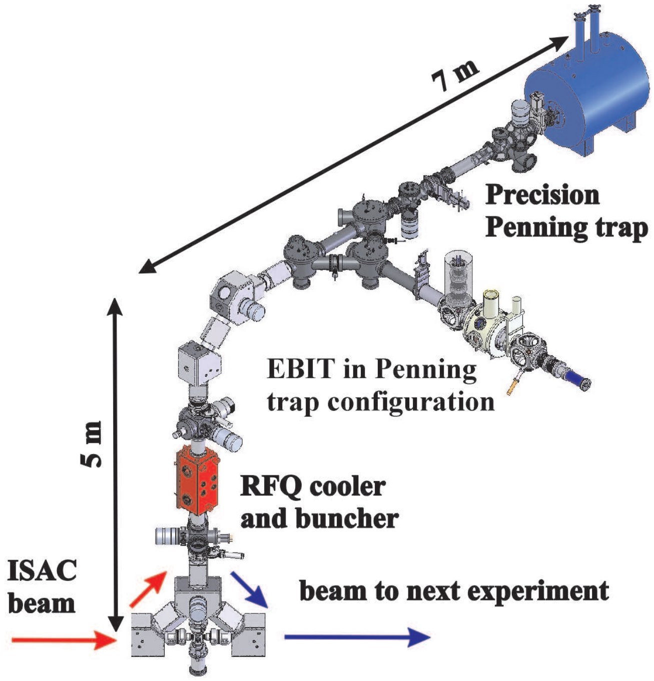

Figure 1: The TITAN mass spectrometer setup at the TRIUMF-ISAC radioactive beam facility. The EBIT is employed in Penning trap mode.

The TITAN set-up is shown in figure 1.

The parent ^{32}Al is expected to be produced in intensities of about 500 ions s^{-1}. The beam will be delivered to the RFQ cooler and buncher and cooled for 10 ms. Then the bunch is delivered to the EBIT, which will collect 100 bunches over one second. The ^{32}Al decays in the EBIT and the daughter ^{32}Si can be recaptured. The maximal kinetic energy of the recoil ions is rather high, at 3.07 keV, due to the Q_β-value of 13.02 MeV. We will use deep trapping potentials (up to 2 kV) to minimize losses due to the recoils. This potential will not be deep enough to capture all isotropically recoiling Si ions, however, radial confinement and additional stopping in the He-buffer gas will lead to a recapture efficiency of about 50%. Initially after the beta-decay the recoils will be doubly charged, which increases the re-capture efficiency. Then they will be cooled using mass selective buffer gas cooling [20], which will also allow for the removal of any remaining isobaric contamination, such as ^{32}Al or others.

Experiments of this kind have been performed at ISOLTRAP [19], where ^{37}K ions were trapped and the recoiling daughter ^{37}Ar nuclei were recaptured in a buffer-gas filled Penning trap with a 100 eV deep potential, with high efficiency. In their case the recoil energy was as high as 650 eV.

The purified sample of ^{32}Si of about 50 ions s^{-1} will be transferred to the Measurement Penning Trap, where the mass will be determined via the TOF-resonance method, in the same fashion as for previous TITAN measurements [21]. The Penning trap system needs to be calibrated with stable isotopes. The excitation time determines the achievable mass resolution, and since in this particular case we are not limited by the half-life, excitation times of 1 s will be used. This will allow us to acheive an uncertainty of 3×10^{-9} with 10 000 cycles, and about 1-2 ions per cycle. In order to verify the precision, we will require five measurements of ^{32}Si (15 hours, with 3 hours per measurement) and reference measurements of about one hour in between, before and after (6 hours).

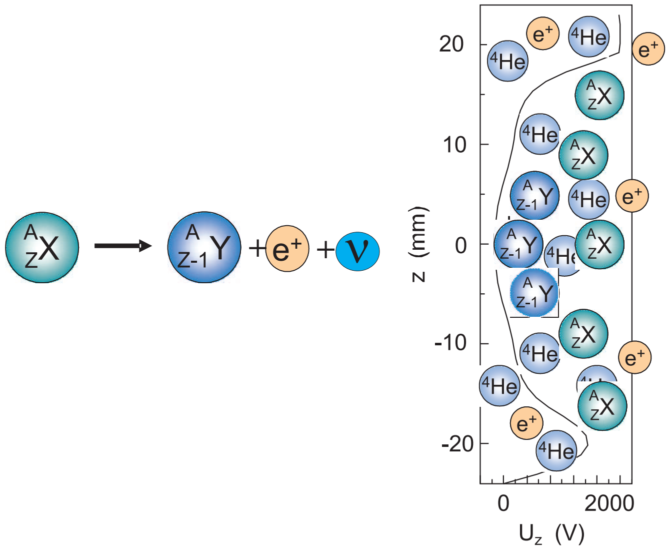

Figure 2: The beta-decay of an element. In the TITAN EBIT, employed in Penning trap mode, and filled with He-buffer gas, the recoil ions can be recaptured.

4 Readiness

The TITAN mass spectrometer has been used for direct measurements copious number of times. This experiment will use the EBIT as an intermediate storage trap, which will allow us to do spectrometry of atomic ions (otherwise not accessible at ISAC) produced by in-trap decay. This is a new technique for TITAN and will require some extra testing and set-up time, once the EBIT and transfer-beamline to the MPET are commissioned in August 2008. We need to develop and commission the mass selective cooling procedure in the EBIT (off-line). The experiment could start first tests as early as Fall 2008. We therefore request for both stage 1 and stage 2 approval for this experiment.

5 Beam time required

For the actual mass measurement we request 4 shifts of Al-beam with an assumed intensity of 300 s^{-1}. The set-up time and mass selective cooling optimization will make up the majority of the requested beam time and is estimated to be 8 shifts. We therefore request a total of 12 shifts.

1. K. Blaum *et al.*, Phys. Rev. Lett. **91**, 260801 (2003).
2. E.G. Adelberger *et al.*, Phys. Rev. Lett. **82**, 1299 (1999).
3. M. Bhattacharya *et al.*, Phys. Rev. C (2008), accepted for publication.
4. B.A. Brown, personal communication.
5. A. García, personal communication.
6. E.P. Wigner, *Proceedings of the Robert A. Welch Conferences on Chemical Research, Houston* (Robert Welch Foundation, Houston, 1957), Vol. 1.
7. S. Weinberg and S.B. Treiman, Phys. Rev. **116**, 465 (1958).
8. W. Benenson and E. Kashy, Rev. Mod. Phys. **51**, 527 (1979)
9. J. Britz, A. Pape and M. Antony, At. Data Nucl. Data Tables. **69**, 125 (1998).
10. C. Yazidjian *et al.*, Phys. Rev. C **76**, 024308 (2007).
11. W.E. Ormand, Phys. Rev. C **55**, 2407 (1997).

12. I.S. Towner and J.C. Hardy, Phys. Rev. C **77**, 025501 (2008).
13. S. Triambak *et al.*, Phys. Rev. C **73**, 054313 (2006).
14. M. S. Antony *et al.* in *Proceedings of the International Conference on Nuclear Physics, Berkeley, 1980* (Lawrence Berkeley Laboratory, Berkeley, CA, 1980), Vol. 1.
15. G. Audi, A.H. Wapstra and C. Thibault, Nucl. Phys. A **729**, 337, (2003).
16. S. Röttger, A. Paul and U. Keyser, IEEE Transactions on Instrumentation and Measurement **46**, 560 (1997).
17. A. Paul, S. Röttger, A. Zimbal and U. Keyser, Hyperfine Interactions **132**, 189 (2001).
18. M. Dombsky, personal communication.
19. A. Herlert et al., New J. Phys. 7, 44 (2005).
20. G. Savard et al., Phys. Lett. A158, 247 (1991).
21. V. Ryjkov et al., Phys. Rev. Lett (2008), accepted for publication.