

# Progress towards precision measurements of $\beta$ -decay correlation parameters using atom and ion traps

**D. Melconian<sup>\*,ab</sup> R.S. Behling,<sup>ac</sup> B. Fenker,<sup>ab</sup> M. Mehlman,<sup>ab</sup> P.D. Shidling,<sup>a</sup> M. Anholm,<sup>de</sup>, D. Ashery,<sup>f</sup> J.A. Behr,<sup>d</sup>, A. Gorelov,<sup>d</sup>, G. Gwinner,<sup>g</sup> K. Olchanski,<sup>d</sup> and S. Smale<sup>d</sup>**

<sup>a</sup>*Cyclotron Institute, Texas A&M University  
College Station, TX 77843-3366 USA*

<sup>b</sup>*Department of Physics & Astronomy, Texas A&M University  
College Station, TX 77843-4242 USA*

<sup>c</sup>*Department of Chemistry, Texas A&M University  
College Station, TX 77843-3012 USA*

<sup>d</sup>*TRIUMF  
Vancouver, BC V6T 2A3 Canada*

<sup>e</sup>*Department of Physics & Astronomy, University of British Columbia  
Vancouver, BC V6T 1Z1 Canada*

<sup>f</sup>*School of Physics and Astronomy, Tel Aviv University  
Tel Aviv, Israel*

<sup>g</sup>*Department of Physics & Astronomy, University of Manitoba  
Winnipeg, MB R3T 2N2 Canada  
E-mail: dmelconian@physics.tamu.edu*

The correlations of the decay products following the  $\beta$  decay of nuclei have a long history of providing a low-energy probe of the fundamental symmetries of our universe. Over half a century ago, the correlation of the electrons following the decay of polarized  $^{60}\text{Co}$  demonstrated that parity is *not* conserved in weak interactions. Today, the same basic idea continues to be applied to search for physics beyond the standard model: make precision measurements of correlation parameters and look for deviations compared to their standard model predictions. Efforts to measure these parameters to the 0.1% level utilizing atom and ion trapping techniques are described.

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\*Speaker.

## 1. Introduction

The primary goal of the Texas A&M University trap (TAMUTRAP) and TRIUMF Neutral Atom Trap (TRINAT) facilities is to search for new physics by pushing the precision frontier. Precision measurements of  $\beta$ -decay correlations of certain nuclei are sensitive to physics beyond the standard model. In particular, pure Fermi decays (which are predicted to be mediated by a vector interaction) are sensitive to possible admixtures of a weak scalar current via the  $\beta - \nu$  correlation parameter  $a_{\beta\nu}$ . Measuring this correlation via the shape of the  $\beta$ -delayed proton energy spectrum from the decay of isospin  $T = 2$  nuclei will be the focus of initial program for the TAMUTRAP facility. The isobaric analogue decay of mixed transitions, such as  $^{37}\text{K}$ , are also sensitive to a variety of new physics (e.g. right-handed currents, tensor interactions, second-class currents, ...) just like the neutron. The TRINAT collaboration has a mature program performing precision  $\beta$ -decay experiments using a magneto-optical trap [1, 2, 3, 4]. We have developed the ability to trap and highly-polarize  $^{37}\text{K}$  using atomic techniques, and have recently taken data for the first-ever measurement of the  $\beta$ -asymmetry parameter,  $A_\beta$ , from laser-cooled atoms. The goal for all of these correlation measurements, both by TAMUTRAP and TRINAT, is to be complementary to high-energy searches which may be realized when reaching a precision of 0.1% [5, 6].

## 2. Ion Trapping with TAMUTRAP

We are in the process of building and commissioning a unique Penning trap system at the Cyclotron Institute on the campus of Texas A&M University. Our initial program will precisely measure the shape of the  $\beta$ -delayed proton energy spectrum from the decay of isospin  $T = 2$  nuclei. Being a pure Fermi transition between  $0^+$  states, the angular distribution of these decays is given simply by [7, 8]

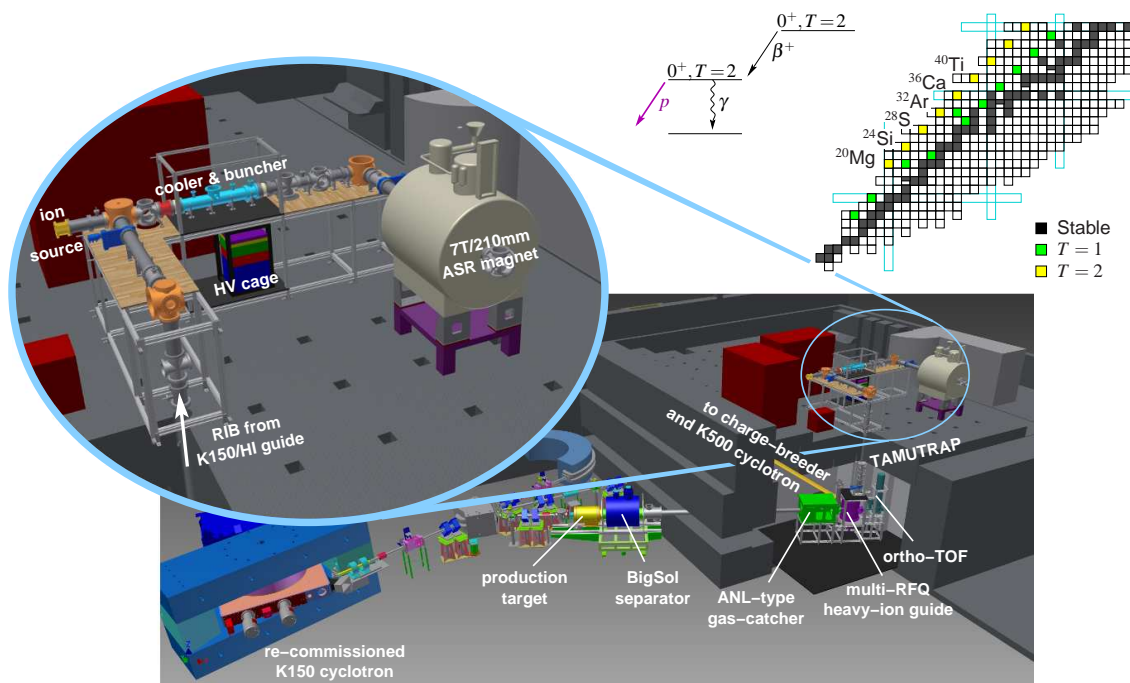
$$dW = dW_0 \xi \left( 1 + a_{\beta\nu} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} \right) \quad (2.1)$$

with

$$dW_0 = \frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_0 - E_e)^2 F(Z, E_e) dE_e d\Omega_e d\Omega_\nu, \quad (2.2)$$

where  $E_e$  and  $p_e$  are the energy and momentum of the  $\beta$ ,  $A_0$  is the maximum energy available to the leptons and  $F(Z, E_e)$  is the Fermi function. The Fermi coupling constant is  $G_F/(\hbar c)^2 = 1.16639(1) \times 10^{-5} \text{ GeV}^{-2}$  (taken from  $\mu$  decay) and  $V_{ud}$  is the up-down element of the Cabibbo-Kobayashi-Maskawa (CKM) mass-mixing matrix. The correlation parameters  $a_{\beta\nu}$  and  $b$  depend on the form of the weak interaction and are particularly sensitive to scalar currents.

One of the most precise limits to date on possible scalar contributions to the predominantly  $V - A$  form of the weak interaction was made by observing the energy spectrum of the  $\beta$ -delayed proton following the superallowed decay of  $^{32}\text{Ar}$  [9, 10]. This 0.5% measurement of the combination of  $\beta - \nu$  and Fierz correlation parameters,  $\tilde{a}_{\beta\nu} \equiv a_{\beta\nu}/(1 + b\langle E_e \rangle)$ , was made by observing only the proton energy in singles, ignoring any information from the  $\beta$ . Using the favourable source conditions of a Penning trap, we plan to improve on this type of measurement by observing the



**Figure 1:** Layout of the TAMUTRAP facility at the Cyclotron Institute, Texas A&M University (see text). The initial program for this Penning trap system will measure the  $\beta$ -delayed protons from the decay of a number of proton-rich  $T = 2$  nuclei as shown by the chart of nuclides (top-right).

$\beta$  in coincidence with the proton. Such a measurement will have an enhanced sensitivity as well as being less susceptible to backgrounds. In order to obtain near  $4\pi$  collection of the protons, we have designed our cylindrical Penning trap to be the world's largest, having an unprecedented inner trap-electrode diameter of 180 mm. Additional scientific capabilities planned for this system are  $ft$ -values, lifetime measurements, mass measurements, and providing an extremely pure, low-energy radioactive ion beam for various other applications.

The general layout of the TAMUTRAP facility and how it fits within the T-REX upgrade of the Cyclotron Institute are shown in Fig. 1. Radioactive ions will be produced via fusion evaporation reactions with a  $^3\text{He}$  gas target using the high-intensity primary beams available from the K150 cyclotron. The reaction products will be separated following the production target using BigSol, a large-acceptance, 7 T solenoidal magnet. The secondary beam will be stopped in the gas-catcher of the heavy-ion guide system, which can then send the rare ions at 15 keV beam energy either to a charge-breeder and the K500 for re-acceleration, or up to the TAMUTRAP facility. The main components of the TAMUTRAP facility are: a radio-frequency quadrupole (RFQ) Paul trap used to cool and bunch the ions, a purification Penning trap for isobar separation, and a novel measurement Penning trap for precision  $\beta$ -decay measurements [11].

Currently, TAMUTRAP is in an ongoing state of design, fabrication, and assembly. Production calculations for the species of interest have been performed using LISE and the predicted beam capabilities of the K150 cyclotron, indicating what rates might ultimately be expected (see Table 1). To complement this, initial production experiments have been performed using the K500 Cyclotron in combination with the MARS spectrometer, in order to verify the cross-sections calculated in

Radioactive ion beam	Primary beam	Calculated cross-section [ $\times 10^{-3}$ mb]	Estimated production rate [ $\times 10^5$ pps]
$^{20}\text{Mg}$	$^{20}\text{Ne}$ @ 24 MeV/u	16.2	14
$^{24}\text{Si}$	$^{24}\text{Mg}$ @ 23 MeV/u	15.5	6.5
$^{28}\text{S}$	$^{28}\text{Si}$ @ 23 MeV/u	4.5	1.5
$^{32}\text{Ar}$	$^{32}\text{S}$ @ 21 MeV/u	7.3	1.4
$^{36}\text{Ca}$	$^{36}\text{Ar}$ @ 23 MeV/u	6.3	2.5
$^{40}\text{Ti}$	$^{40}\text{Ca}$ @ 23 MeV/u	1.7	0.7

**Table 1:** Calculated production rates of the  $T = 2$  nuclei of interest for the initial program of TAMUTRAP. All isotopes are planned to be produced using fusion-evaporation reactions with a  $^3\text{He}$  gas target.

LISE. The data for this work is still being examined. Efficiency and rate-handling estimations for the entire beamline following the target chamber have been considered, yielding a total predicted efficiency of around 0.8%. Other simulation work that is currently ongoing includes geometric efficiency calculations for the proposed measurement and initial simulations and trial analysis of the decay of interest.

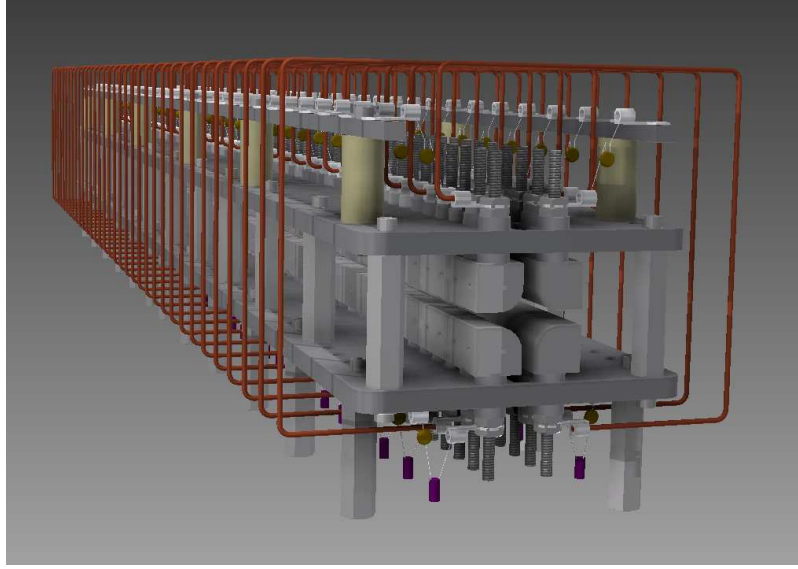
In addition to production and other simulation work, there has been significant construction and testing on critical hardware for the TAMUTRAP experiment. A prototype version of the RFQ cooler and buncher, including most ancillary systems and equipment, was assembled and optimized in continuous mode using an offline ion source. The total transmission was found to be on the order of 25% in this mode. This relatively low efficiency is dominated by variations in the electrode distances; we are designing a new support and alignment structure for the RFQ, as shown in Fig. 2. Commissioning of this much more robust and sturdy RFQ is planned to be completed within one year. The electronics for the prototype RFQ were found to work according to specifications, yielding up to 160 V peak-to-peak at frequencies between 0.5 – 1.5 MHz.

In addition to the RFQ, a beam diagnostic station based on a Faraday cup and micro-channel plate (MCP) detector has been installed. Testing of these devices is currently ongoing, using the same offline ion source as described above. An emittance measurement add-on based on the pepper-pot technique has been fabricated, and will be implemented in the future.

The immediate outlook for the TAMUTRAP facility involves completing the redesign of the RFQ and performing more realistic simulations of the decays of interest, in addition to continuing development of various beamline systems. In particular, simulations are planned with GEANT4, and timing and control systems for the beamline are being developed around a National Instruments FPGA controlled by LabView.

### 3. Atom Trapping with TRINAT

Magneto-optical traps (MOTs) provide an excellent source of radioactive atoms which can be easily polarized using atomic techniques. The isotope currently being studied by the TRINAT collaboration is the  $\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$  mixed Fermi/Gamow-Teller isobaric analogue decay of  $^{37}\text{K}$ . In this case, the angular distribution of the decay as given in Refs. [7, 8] is much richer given that the



**Figure 2:** AutoCAD design of the RFQ cooler and buncher. The 15 keV ions from the heavy ion guide will be cooled via collisions with the  $\sim 10^2$  atm He buffer gas, and collect at the end of the 28-electrode structure at the bottom of the DC potential well. The ejected bunched beam will have an energy spread of 5 – 10 eV and a time spread of 1.0 – 1.5  $\mu$ s.

$$\begin{aligned}
 a_{\beta\nu} &= \frac{1-\rho^2/3}{1+\rho^2} &= 0.6580(61) \\
 b &= 0 \text{ (sensitive to scalars and tensors)} \\
 A_{\beta} &= \frac{-2\rho}{1+\rho^2} \left( \sqrt{3/5} - \rho/5 \right) = -0.5739(21) \\
 B_{\nu} &= \frac{-2\rho}{1+\rho^2} \left( \sqrt{3/5} + \rho/5 \right) = -0.7791(58) \\
 c_{\text{align}} &= \frac{4\rho^2/5}{1+\rho^2} &= 0.2053(36) \\
 D &= 0 \text{ (sensitive to imaginary couplings)}
 \end{aligned}$$

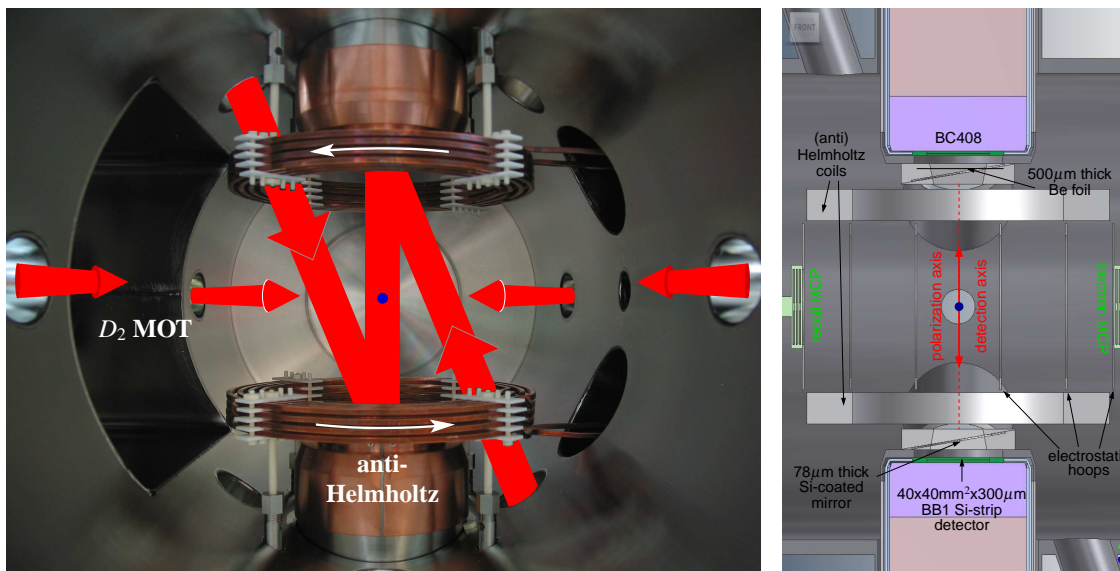
**Table 2:** Standard model predictions of the correlation parameter values for the decay of  $^{37}\text{K}$ . The uncertainties quoted result from the  $\pm 1.2\%$  precision to which the observed  $ft$  value determines  $\rho$ .

nucleus may be polarized and/or aligned:

$$\begin{aligned}
 dW &= dW_0 \xi \left[ 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \frac{\vec{I}}{I} \cdot \left[ A_{\beta} \frac{\vec{p}_e}{E_e} + B_{\nu} \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right] \right. \\
 &\quad \left. + c_{\text{align}} \left\{ \left[ \frac{\vec{p}_e \cdot \vec{p}_\nu}{3E_e E_\nu} - \frac{(\vec{p}_e \cdot \hat{i})(\vec{p}_\nu \cdot \hat{i})}{E_e E_\nu} \right] \times \left[ \frac{I(I+1) - 3\langle (\vec{I} \cdot \hat{i})^2 \rangle}{I(2I-1)} \right] \right\} \right] \quad (3.1)
 \end{aligned}$$

where again  $dW_0$  is given by Eq. (2.2). Being a mixed decay, the correlation parameters in this case are all functions of  $\rho \equiv C_A M_{GT} / C_V M_F$  (see Table 2), where  $C_A$  ( $C_V$ ) are the axial-vector (vector) semi-leptonic form factors and  $M_{GT}$  ( $M_F$ ) are the Gamow-Teller (Fermi) matrix elements of the decay.

As in previous experiments, we continue to employ a double-MOT system [12] to increase efficiency and remove backgrounds from untrapped atoms. Figure 3 shows the improved geometry



**Figure 3:** Side views of TRINAT's detection chamber. On the left is a picture as viewed from the recoil MCP toward the electron MCP. The two re-entrant flanges house the  $\beta$  telescopes. Also visible are the water-cooled leads for the coils which provide the Helmholtz (optical pumping) and anti-Helmholtz (magneto-optical trapping) fields. On the right is a schematic diagram of a view rotated  $-90^\circ$  from the picture on the left. See the text for a description of the elements shown.

we have recently commissioned which is optimized for measuring polarized correlation parameters. The two  $\beta$ -telescope detectors consist of a  $300\ \mu\text{m}$ -thick double-sided Si-strip detector and a BC408 plastic scintillator; this will make the polarization axis – the sign of which is determined by the polarization of the laser beams – equivalent to the  $\beta$  detection axis. This is an *ideal* geometry for measuring the  $\beta$  asymmetry, where one has the ability to flip the initial nuclear polarization on timescales of a few milliseconds. The only material between the source and detectors is a thin mirror and a  $0.1\ \text{mm}$  Be foil to separate the ultra-high vacuum of the chamber from the detector ports.

On the right panel of Fig. 3 one can see the two micro-channel plate detectors we have placed; the view in the left pane is from one to the other. Electrostatic hoops generate a uniform electric field whose function is threefold: (1) to increase collection efficiency of the recoiling  $^{37}\text{Ar}^+$  ions into the recoil MCP, (2) to help separate their different charge states of the recoiling ions, and (3) to accelerate the negatively charged shake-off electrons in the opposite direction onto an  $e^-$  MCP. The addition of a pulsed  $355\ \text{nm}$  laser which is able to photoionize atoms in the  $P_{1/2}$  excited state (but not the  $S_{1/2}$  ground state) allows us to monitor the excited state population and cloud characteristics (size, position, temperature) in the following way: when a neutral atom is photoionized, an ion is produced which will be accelerated onto the position-sensitive recoil MCPs; gating on the time relative to the laser pulse results in a very clean, essentially background-free signal.

The MOT does not provide a polarized source of atoms, so we release the atoms, quickly polarize them using optical pumping techniques, make our asymmetry measurements, and then turn the trap back on to recollect the atoms before they expand too far and are lost. Every  $700\ \text{ms}$  we switch the polarization state of the optical pumping light and hence flip the nuclear spin of

the  $^{37}\text{K}$ . Unlike many other polarized experiments, we are able to measure the polarization of the cloud *in situ* by fitting the observed  $P_{1/2}$  excited state populations as a function of time to a optical-Bloch equation model of the optical pumping process. Using  $^{41}\text{K}$ , a stable isotope which has a very similar electronic structure to  $^{37}\text{K}$ , we have demonstrated the ability to polarize laser-cooled atoms to  $99.4 \pm 0.4\%$  nuclear polarization.

We collected data for the first time with the new system in December 2012. Relative to the last precision measurement on radioactives, many extensive improvements were made to the system: new detection chamber, adopting an AC-MOT [13] over the traditional DC-MOT to reduce eddy currents, installing new  $\beta$  detectors, and upgrading from CAMAC to VME. Given all these major changes, the goal of the December run was not only to show physics improvement by publishing a meaningful value for the  $\beta$  asymmetry but to also to demonstrate engineering improvements and characterize the system that the collaboration will now use to produce more precise measurements in the future. The whole system operated and ran in according to the design specification with the exception of the electrostatic field: sparking limited us to 350 V/cm instead of our goal of 1 kV/cm.

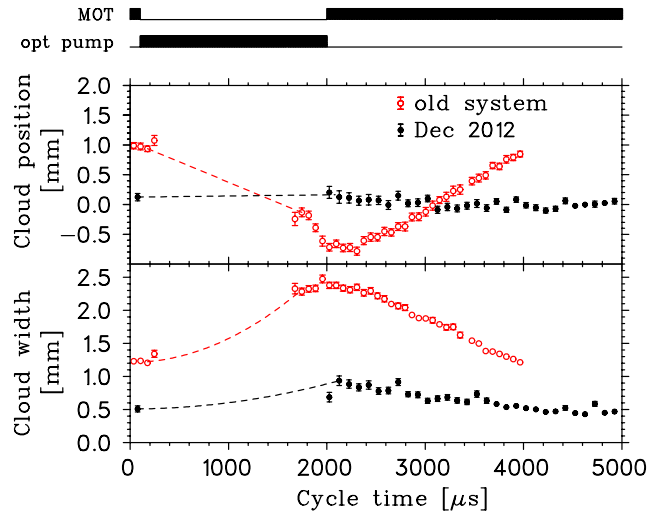
One clear indication of the improvements made is in the size and position of the cloud during our trapping/polarizing cycle. As one can clearly see in Fig. 4 where we plot the cloud characteristics as determined by the photoion data, we have greatly improved our control and temperature of the atom cloud. Plotted are the cloud position and size as determined by the position of photoions in the MCP detector. We start with trapped atoms, release them by turning off the MOT beams and optically pump to polarize the laser-cooled cloud. Before the cloud expands too much, we turn off the optical pumping beams and turn the MOT beams back on to re-trap atoms before they escape. However, it is now clear that with the 1-inch diameter optical-pumping and MOT beams we have, we could have increased our duty cycle dramatically by reducing the time we spent re-trapping the atoms.

Figure 5 shows the  $\beta$  spectrum during polarized times (300 – 2000  $\mu\text{s}$ ) in one of the scintillators requiring a coincidence with (i) a  $\beta$  in the  $\Delta E$  Si-strip detector and (ii) a shake-off electron in the  $e^-$  MCP to ensure the decay occurred from the trap (rather than, e.g., from the walls or the mirror in front of the telescope). Requiring an anti-coincidence with the opposite  $\beta$ -telescope had a negligible effect on the spectrum. The overlaid histogram is a GEANT4 simulation where no backgrounds or other effects have been added; the comparison is the raw data to the corresponding simulated data. The analysis is preliminary at this stage, however one can already see that the spectrum—even the 511 keV Compton edge from the annihilation radiation—is reproduced *extremely* well in the monte carlo.

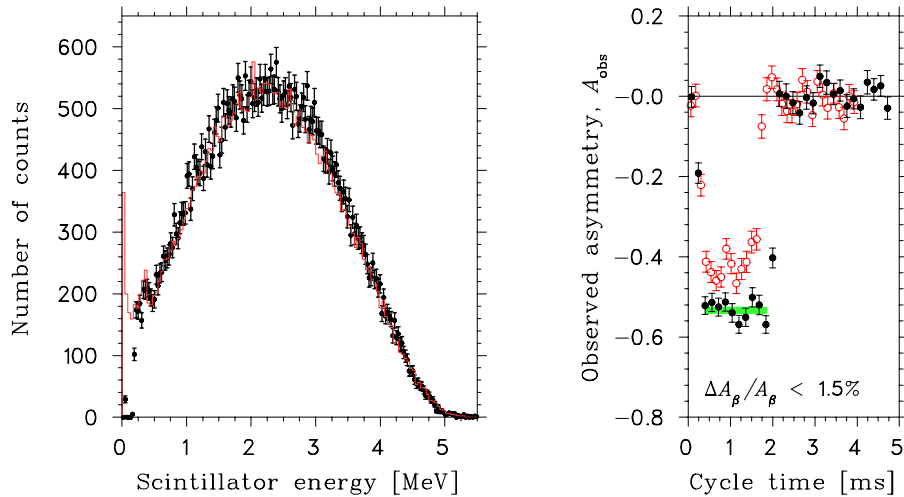
The right panel of Fig. 5 shows a preliminary analysis of the asymmetry observed in the Dec. 2012 run via the “super-ratio” technique. The super-ratio,  $R$ , is defined in terms of the measured energy-dependent detector count rates for the two spin states,  $r_i^\pm(E)$ , to be

$$R = \frac{r_1^-(E_e) r_2^+(E_e)}{r_1^+(E_e) r_2^-(E_e)}. \quad (3.2)$$

Based on the angular distribution, Eq. (3.1), the  $\beta$  asymmetry parameter may be extracted from the



**Figure 4:** Position and size of the  $^{37}\text{K}$  cloud as a function of time in the trapping/polarizing cycle before and after improvements to the system. There are not enough photoions produced during optical pumping times since so few atoms get excited to the  $P_{1/2}$  state, whereas atoms get excited often during MOT times. One can clearly see that the cloud position was much more stable in the latest run. Furthermore, based on the size and expansion of the cloud when the trapping MOT beams are off, the cloud is half as large and there is a  $4\times$  reduction in its temperature.



**Figure 5:** Energy spectrum in one of the scintillators (left) and preliminary super-ratio asymmetry (right) for the Dec. 2012 run. A GEANT4 simulation of the  $\beta$  spectrum is overlaid, with no background subtracted from the data or added to the simulation, demonstrating we have an extremely clean and well-understood system. Analysis of the super-ratio is still in progress, but preliminary analysis of the Dec. 2012 data (filled circles) show a dramatically improved asymmetry compared to the old system (open circles) when  $B_V$  was measured [3].



super-ratio according to

$$\frac{1 - \sqrt{R}}{1 + \sqrt{R}} = A_{\text{obs}}(E_e) = \langle P \rangle A_{\beta} \frac{v}{c} \langle \cos \theta \rangle, \quad (3.3)$$

where  $P$  is the average nuclear polarization,  $v/c$  is the velocity of the  $\beta$ , and  $\langle \cos \theta \rangle$  is the average value of  $\cos \theta$  integrated over the  $\beta$ -telescopes' angular acceptance. This method for extracting  $A_{\beta}$  is superior over a simple asymmetry because many systematic effects cancel to first order in the super-ratio, including spin-dependent and detector efficiencies. As expected, the observed asymmetry is large during polarized times and consistent with zero during trapping times. The open circles represent the  $\beta$  asymmetry observed in the old system when we measured the neutrino asymmetry [3] before we added the shake-off electron detector; in that case the asymmetry was significantly attenuated from unpolarized atoms that did not decay from the trap, precluding us from making a precision measurement of  $A_{\beta}$ . Our improved system ensures the  $\beta$  decays occurred from trap and already show a much higher asymmetry. The statistical uncertainty in the observed asymmetry is below 1.5%, however analysis of the systematics remains on-going.

#### 4. Conclusions

Ion and atom traps provide a powerful tool for performing precision  $\beta$ -decay measurements of angular correlations. These correlations are sensitive to the form of the weak interaction and may be used to complement searches for new physics at colliders if precisions of 0.1% may be reached. We have presented progress on two efforts pushing the precision frontier as beyond the standard model tests: the TAMUTRAP facility at the Cyclotron Institute which will measure  $\beta - \nu$  correlations in proton-rich nuclei using a Penning trap; and the TRINAT facility at TRIUMF which has recently measured the  $\beta$  asymmetry in the mirror decay of  $^{37}\text{K}$ .

#### 5. Acknowledgments

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