TRIUMF — RESEARCH PROPOSAL	Experiment no.	Sheet 1 of 17

Title of proposed experiment:

Upgrade of ^{38m}K β-ν correlation

Name of group: TRINAT

Spokesperson for group: J.A. Behr

E-Mail address: behr@triumf.ca

Fax number: (604)222-1074

Members of the group (name, institution, status, per cent of time devoted to experiment)

Name	Institution	Status	Time
C. Höhr	TRIUMF	Postdoc Research Associate	100%
New. Student	UBC	Student	or 100%
or R. Pitcairn	UBC	M.Sc. Student–>Ph.D.	or 100%
or D. Roberge	UBC	M.Sc. Student–>Ph.D.	100%
J. Behr	TRIUMF	Research Scientist	100%
M. Pearson	TRIUMF	Research Scientist	40%
A. Gorelov	S.F.U.	Ph.D. Student	E715
K.P. Jackson	TRIUMF	Emeritus Research Scientist	30%
D. Ashery	Tel Aviv Univ.	Professor	20%
P. Bricault	TRIUMF	Research Scientist	5%
M. Dombsky	TRIUMF	Research Scientist	5%
F. Glück	Budapest	Theorist	theory
D. Melconian	U. Washington	postdoc	5%

Start of preparations: 2005

Date ready: 2006

Completion date: 2007-8

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
30+20	BL2A/ISAC/TiC target	No

The TRIUMF Neutral atom trap collaboration has pioneered the direct measurement of β^+-ν angular distributions by measuring the momentum of the few 100-eV energy recoiling nucleus in coincidence with the positron.

We have published the best limits on general scalar interactions coupling to the first generation of particles [A. Gorelov *et al.* Phys. Rev. Lett. **94** 142501 (2005).] We propose to improve the overall accuracy of this β-ν correlation experiment by a factor of 3. We also would extend it to lower β energy to improve sensitivity to the scalar-vector Fierz interference term and hence gain linear sensitivity to certain types of scalars, reaching accuracy directly competitive with the Q-value dependence of $0^+ \rightarrow 0^+$ ft values.

Although there are many direct and indirect constraints on scalar interactions, there is little theoretical guidance about scalar interactions and so direct experiments with general sensitivity are still of great interest. The theoretical interpretation of the β-ν correlation in our case is independent of nuclear structure calculations. The radiative corrections (mostly real γ emission via bremsstrahlung) make an 0.2% correction and are reliable to an order of magnitude better than needed.

ISAC has demonstrated ^{38m}K yields 5x greater than those for the published experiment, and we have also improved our collection efficiency by 3x by adding another ring laser. Most of our systematic errors are given by statistically limited fits of different aspects of the data in situ. We have the best experiment and have good ideas on what to fix and upgrade to make it considerably better.

Experimental area

ISAC TRINAT

Primary beam and target (energy, energy spread, intensity, pulse characteristics, emittance)

500 MeV protons, TiC target, 45 μA

Secondary channel ISAC LEBT

Secondary beam (particle type, momentum range, momentum bite, solid angle, spot size, emmittance, intensity, beam purity, target, special characteristics)

^{38m}K 5x10^7/sec

TRIUMF SUPPORT:

- continued support of existing TRINAT lab at ISAC

NON-TRIUMF SUPPORT

- NSERC TRINAT project grant (J.A. Behr, *et al.*); present support through April 2006. Continuing support reapplied for.

Radiation: ISAC target and LEBT operation to TRINAT clean room in ISAC. J.A. Behr safety officer. ^{38}K g.s. contaminant 2.17 MeV γ creates local safety hazard controlled by personnel access, which we have demonstrated in the past. The ^{38}Ar daughter is stable.

Procedures for safety of the laser systems preclude access to the TRINAT clean room at ISAC. J.A. Behr laser safety officer.

1 Scientific Justification

TRIUMF's neutral atom trap (TRINAT) (see Fig. 1) captures radioactive atoms in a 1 mm-sized cloud using the pressure of laser light, with goals of precision Standard Model weak interaction tests in both the charged and neutral current sectors. The low-energy recoiling nuclei produced in nuclear β decays freely escape the trap, and by measuring their momenta in coincidence with the β, the ν momentum has been deduced more directly than in previous experiments. We have pioneered these techniques at TRIUMF/ISAC.

A very attractive aspect of the scalar search described here is that it is free of nuclear structure-dependent corrections. The ^{38m}K decay is one of the well-characterized superallowed $0^+ \to 0^+$ decays (see Fig. 1). The branch to the excited state is known to decay cleanly to the ground state, with experimental limits on excited-state branches of $<2\times10^{-5}$ [1]. The 'recoil-order' corrections to the allowed approximation are small, $<3\times10^{-4}$, and are calculable without nuclear matrix elements [2]. Radiative corrections, mostly due to the distortion of the momenta by bremsstrahlung production of real photons, are at 0.2% level but can be calculated to accuracy an order of magnitude better, and we include this in our Monte Carlo with assistance from F. Glück [3].

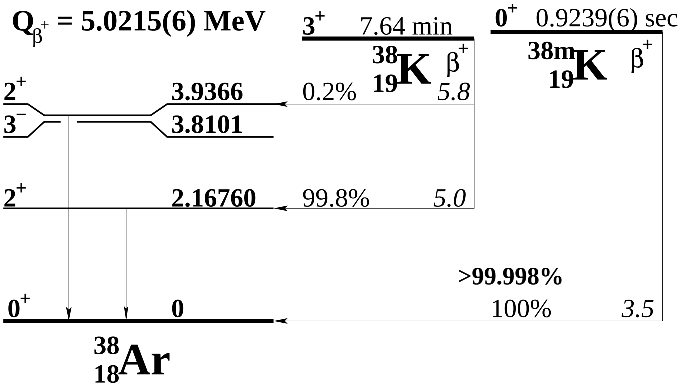

Fig. 1. β-decay of ^{38m}K and ^{38g}K, which is a contaminant in the mass-separated beam.

1.0.1 β-ν correlations in more detail

The weak interaction is mediated by vector bosons with spin one. Because the leptons are produced with opposite helicity, this implies a β-ν angular distribution

$$P(\theta_{\beta\nu}) = 1 + b\frac{m_\beta}{E_\beta} + a\frac{v_\beta}{c}\cos\theta_{\beta\nu}$$

which vanishes at 180^o for spin-0 nuclei decaying to spin-0 nuclei, i.e. a=1 and b=0. If a spin-0 boson were exchanged instead, then the leptons have the same helicity, the leptons cannot be produced in the same direction, and a=-1. This is true in the allowed approximation, where no orbital angular momentum is carried off by the leptons. L=1 terms would change the nuclear parity, so the next-order terms are L=2 and do not enter until 10^{-6} level. This simple argument is rigorous: note that it is independent of isospin mixing with other 0^+ states. The dependence on four-fermi coupling constants in the notation of Ref. [10] is

$$a = \frac{|C_V|^2 + |C'_V|^2 - |C_S|^2 - |C'_S|^2 + (\alpha Z m_\beta / p_\beta) 2\ Im(C_S C_V^* + C'_S C'_V *)}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2}$$

$$b = \frac{-2\sqrt{1 - \alpha^2 Z^2}\ Re(C_S C_V^* + C'_S C'_V *)}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2}$$

There is sensitivity to imaginary (time-reversal-violating) terms that is very interesting. It is nevertheless instructive to show the simple expression assuming the constants are real, and that C'_V=C_V (no vector current coupling to right-handed ν:) and even set C_V=1:

$$\begin{aligned} a = (2 - (|C_S|^2 + |C'_S|^2))/(2 + |C_S|^2 + |C'_S|^2) \approx 1 - (|C_S|^2 + |C'_S|^2) \\ b = -2\sqrt{1 - (\alpha Z)^2} Re(C_S + C'_S)/(2 + |C_S|^2 + |C'_S|^2) \end{aligned}$$

The Hamiltonian is regrouped by Herczeg [6]:

$$H_S = [(C_S + C'_S)\bar{e}(1 - \gamma_5)\nu_e^{(L)} + (C_S - C'_S)\bar{e}(1 + \gamma_5)\nu_e^{(R)}]\bar{u}d,$$

making it clearer that the coupling combination $C_S + C'_S$, which is constrained by b, couples to standard model left-handed ν's. The combination $C_S - C'_S$ describes scalars coupling to right-handed ν's and must be constrained by a.

By measuring the β-ν correlation coefficient of ^{38m}K and comparing it to the standard model expectation value of 1, we have searched for a scalar interaction contributing to β decay.

Although the coupling of the scalars in many standard model extentions— like the charged Higgs— scale with the fermion masses and therefore have small couplings to the 1st generation, "...this is partially maintained in the MSSM and simple two Higgs doublet models, but usually not in more complicated Higgs models." [5] The best general limits on first generation scalar interactions still come from nuclear β decay [6].

Our experiment places limits on scalar bosons with mass/coupling ratios $\sim$ 3 times the mass of the W. a is sensitive to the parameter combination $|C_S|^2 + |C'_S|^2$ [10], describing scalars with all possible couplings to ν helicity and time reversal properties. That makes it complementary to the limits on the Fierz interference term b (see next paragraph), and to strong indirect limits from higher-order corrections to $\pi \rightarrow e\nu$ decay in an effective field theory analysis [11].

Fierz term b In addition to improving the measurement of a, we will extend the measurements to lower E_β to gain sensitivity to the Fierz interference term b, with a goal of achieving competitive accuracy to the Q-value dependence of the world average of $0^+ \rightarrow 0^+$ ft values, b_F=0.0024(28) [14]. Previous direct experiments have attempted this by measuring the detailed β energy spectrum. Our technique would measure the angular distribution as a function of β energy, which has much less dependence on detector E_β reponse. We intend to reduce dependence on β energy calibration by using the other kinematic variables to determine it. This observable is sensitive to $C_S + C'_S$, only describing scalars that couple to Standard Model left-handed ν's, but with linear sensitivity to the small quantity. The world average can be affected by errors in isospin mixing or masses in separate shells: the present Savard *et al.* result, incorporating new advances in mass measurements, moved the Fierz centroid by 1 σ (see Fig. 2) while roughly preserving the error. It would be advantageous to make a direct measurement within one experiment that is independent of isospin mixing calculations in different shells.

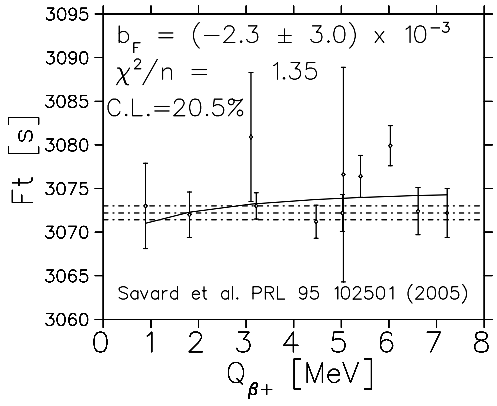

Fig. 2. One test of CVC: our reproduction of the Ref. [14] fit of a Fierz scalar-vector interference term, which modifies the superallowed ft phase space by m/E_β. Our goal is to achieve similar accuracy within one β-ν correlation experiment.

Our present statistical error on the Fierz term is about 4 times larger than that of Ref. [14]. Our upgraded experiment would approach their sensitivity.

Comparison with other results The best previous β–ν experiment was the the Seattle/Notre Dame/ISOLDE collaboration's β-delayed proton decay of ^{32}Ar, with published result $a = 0.9989 \pm 0.0052 \pm 0.0039$ [17]. (This method depends strongly on Q-value, and mass re-measurements mean it must be re-evaluated [18].) They plan a β-proton coincidence experiment to reduce this dependence on Q-value [A. Garcia, private communication]. Other competition include the WITCH Penning trap/recoil momentum spectrometer coming on-line at ISOLDE, which will measure the recoil momentum independent of the β's but also be vulnerable to the recoil dependence of shakeoff. A β-γ Doppler shift measurement in a Paul ion trap at Argonne is coming on-line [N. Scielzo, private communication]. The advantage of our present method over these experiments is our redundant determination of kinematic variables from the β decay process, allowing us to measure detector response functions from the data itself and to exclude backgrounds. We also precisely determine trap location and size by photoionizing the neutral atoms and detecting them in our apparatus.

Loop corrections to ν masses: Non-standard model scalar and tensor interactions may be strongly constrained by effective field theory order-of-magnitude estimates of their two-loop corrections to ν masses [23]. The treatment is not gauge invariant and there are other technical difficulties, but these are in the process of being corrected [M. Ramsey-Musolf, priv. comm.]. This paper assumes m_ν<0.23 eV from WMAP, a premature and paradigm-dependent but perhaps eventually correct assertion. Neutrino mass constraints from tritium β decay are at 3 eV, and using that mass the Ito/Prézeau limits on tensors are poorer than present experiments, while their limits on scalars that couple to wrong-handed ν's are roughly an order of magnitude better than ours.

The constraints are on S,T interactions that couple to wrong-handed neutrinos, so they are complementary to b and a measurements.

Fine-tuning and cancellation of terms can happen in explicit models that will escape constraints from such effective field theory approaches. The work should encourage theorists to work out the constraints from neutrino mass terms on explicit models of scalar and tensor interactions. Direct experiments remain useful.

Scalar form factor Experiments in nuclear β-decay measure some combination of $|C_S|$ and $|C'_S|$. If they are nonzero, the standard model is violated.

For completeness, we mention that in order to interpret these coupling constants in terms of an explicit model of a quark-lepton interaction, then one needs corrections termed "form factors". This is because scalar currents are not conserved (in the sense that vector currents are, so that quark-lepton vector couplings immediately translate to nuclear β decay strengths). Herczeg [6] defines the quantity $g_S(q^2)$ needed in terms of a matrix element involving quark spinors u and d, nucleon spinors u_p and u_n, and nucleon wavefunctions:

$$\langle p|\bar{u}d|n\rangle = g_S(q^2)\bar{u}_p u_n$$

This is not related to an experimentally observable quantity, so it is difficult to assess the accuracy of theory. Herczeg lists a quark model calculation value of 0.6 [7], and estimates an error that is rather large, putting the value between $0.25 < g_S < 1$. A more recent lattice gauge theory calculation implies 0.63±0.09 (the error is a technical error and is not necessarily indicative of the actual theory error) [8]. The quantity is of some interest from the point of view of nucleon structure in medium and nuclear saturation and is essentially the quantity C_σ calculated to be 0.4 [9]. Jennings suggests a similar nucleon-nucleus effect of order 10-15% (private communication). Pospelov (private communication) says the running with q^2 is well-known in the literature: the value decreases somewhat as one goes to high energy, which favors somewhat β decay. It is plausible that if a positive signal were seen, then more interest would be generated.

2 Description of the Experiment

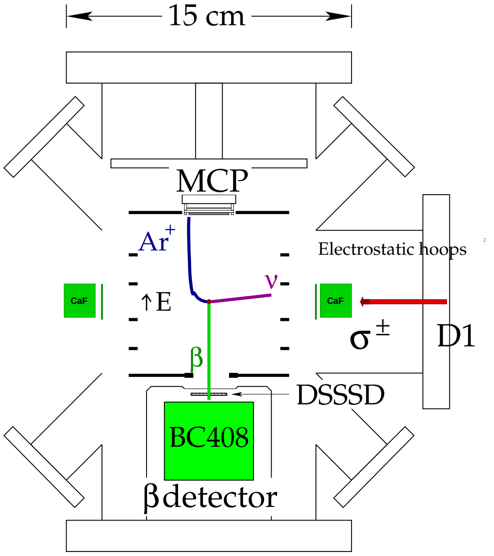

Fig. 3. TRINAT configuration for the detection magneto-optical trap. A uniform electric field collects charged recoil ions to a microchannel plate. TOF and position on MCP determine original recoil momentum, which in coincidence with β energy and position in the DSSSD/plastic detector measures ν momentum. Plastic/CaF$_2$(Eu) phoswiches are along polarization axis for polarized experiments.

The detection trap of our apparatus is shown in Fig. 3. A scatter plot of typical data is shown in Fig. 4.

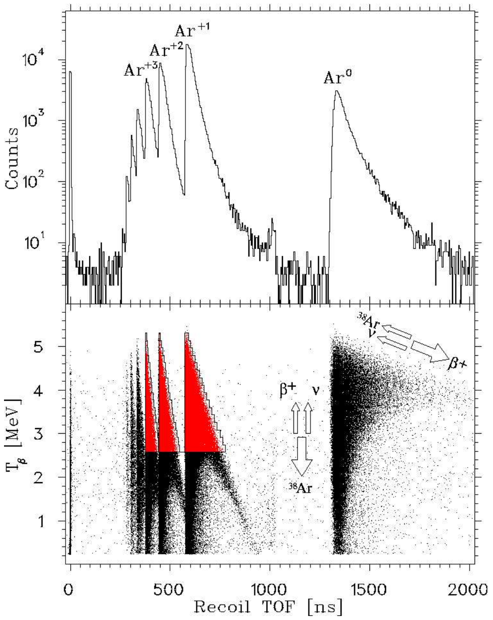

Fig. 4. Bottom: Scatter plot of recoil TOF vs. T_β with one dot shown for each of 500 000 events. The suppressed back-to-back lepton emission produces longer recoil TOF. The E field separates the Ar charge states. The analysis cuts are shown. Top: TOF projections of the 2D scatter plot. The 0.1% background at TOF≈1020 ns is from β's scattering off the MCP into the β telescope and can be rejected kinematically.

We have published the best measurement of a pure Fermi β-ν correlation parameter a= 0.9981±0.0030±0.0037 [4], in agreement with the Standard Model prediction a=1. We analyzed data taken in October 2000 in two ways:

- Method I) fitting the experimental time-of-flight spectra of the recoils as a function of β energy. At fixed E_β, the TOF of the recoil is monotonic with the ν angle of emission. Separating into E_β bins avoids overlapping all of these effective ν angle spectra and diluting sensitivity. Results are in Fig. 5, top pair.

- Method II) Reconstructing the β-ν angle from the position and energy information in both detectors (see Fig.5 bottom pair). This method gives a consistent result. This method has great power to simultaneously extract certain systematic physics errors.

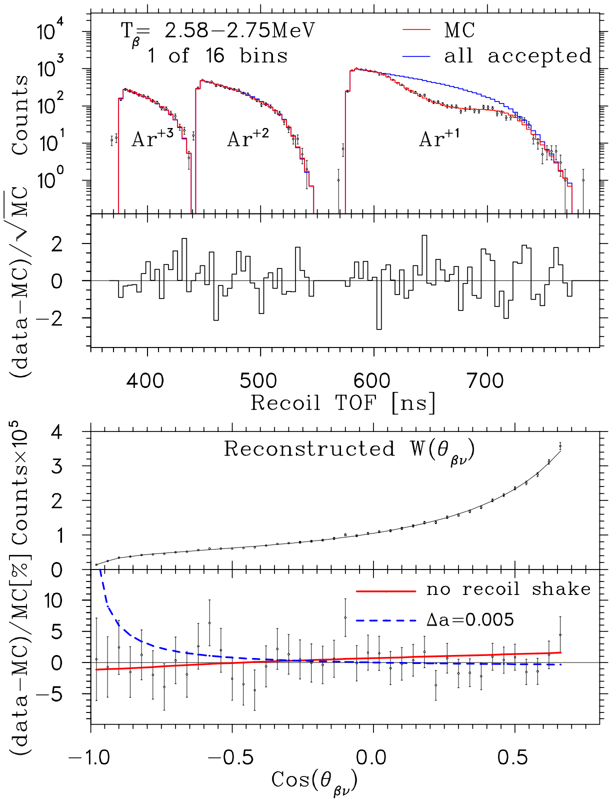

Fig. 5. Top pair: Partial result of method I, a fit of recoil TOF for one of 16 E_β bins. The overall confidence level of the fit is 52%. The dip in Ar^{+1} is from the finite MCP size, and the dashed curve shows a simulation with a larger MCP that will reduce this systematic effect.
Bottom pair: Results of fit method II. Angular distribution of ν's in ^{38m}K decay, as reconstructed from the other kinematic observables without E_β. Lowest figure shows sensitivity to a and ability to simultaneously fit for a and for the dependence of recoil charge state on recoil momentum.

Technical features TRINAT can determine detector response functions in situ from the data itself. This is typically done in high-energy experiments but never before for low-energy β decay. Fig. 6 shows the energy response of the β detector to what would be monoenergetic β's as determined from the other kinematic observables. Similarly, TRINAT has constrained the admixture of possible MeV-mass sterile ν's with the electron ν using the equivalent of a high-energy missing-mass construction [13].

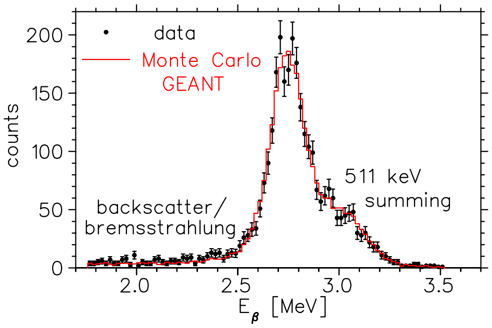

Fig. 6. Energy response of the β^+ detector to 'monoenergetic' β^+'s as determined from the other observables.

2.1 Possible systematic effects from physics

Recoil energy-dependent e$^-$ shakeoff A potential systematic physics error for our method is that the final charge state of the recoiling atom should have a small but nonzero dependence on its velocity. This effect will distort the recoil energy spectrum by (1+s E_{recoil}/E_{max}), in a simple argument based only on the sudden approximation [19,21] independent of the details of the atomic physics calculation. With this parameterization, the shakeoff effect can be fit simultaneously with the a and b parameters. We have done this using both methods I and II (see Fig. 5), finding an effect consistent with zero and with upper limit [4,12] consistent with the rough estimate in Ref. [21]. The correction is small and statistics-limited in its determination. The best ^{6}He β-ν experiment [20] succeeded in extracting this effect while only measuring the recoil momentum spectra as a function of charge state. We also expect to be able to do this in atomic e$^-$-recoil coincidence measurements (see below).

Dependence on atomic density Berkeley has seen evidence for a systematic change in a with density of ^{21}Na atoms in the MOT [22]. Their suggested plausible mechnism involves the formation of molecular dimers from photoassociation. The rate of molecule formation r_{mol} would scale linearly with density. We run at $\sim$1/500 the density. The probability for an atom to form a dimer before decaying will be proportional to r_{mol}/r_{decay}, and the ratio of decay rates is an additional 1/20. So for the simplest scalings, we expect to be down by 10^{-4} in this effect. Nevertheless, the e$^-$-recoil coincidence would provide a high-statistics method for us to test this for the upgraded experiment.

Shakeoff e$^-$ momentum Shakeoff e$^-$s are generally believed to have energies similar to their binding energies, which in our case would mean $\sim$ 15 eV. A 100 eV shakeoff e$^-$ would have momentum $p_e \approx 0.01$ MeV/c, or 2% of the momentum of 0.5 MeV/c recoils of interest in Fig. 8. We can make an adequate determination of the shakeoff e$^-$ energy spectrum by measuring the ratio of recoil-e$^-$ coincidence rate to photoelectron rate as a function of MCP front plate voltage. We have a grid in front of the electron MCP that will keep the electric field seen by the ions constant. We have a pulsed laser that photoionizes about one part per million of the atoms, to determine the cloud shape and location, and this provides a simultaneous calibration source of 1 eV electrons. Recoil TOF will determine where we are within the cloud, and at our present field we would reach about 10 eV energy resolution, smaller if we lower the electric field. A good measurement would be unique and has some biomedical interest (although an electron-capture decay would be more interesting), as shakeoff e$^-$s have ranges matched to DNA strand lengths [24] and there is very little direct experimental information.

3 Proposed Upgrade

We intend to improve this accuracy by a factor of 3. ISAC is now producing five times the yield of ^{38m}K, and we have more laser power and can trap three times more.

Most of the systematic errors are determined by statistics-limited data evaluation. One example: the charge state of the recoil can depend on its momentum by shaking off different numbers of e$^-$s. We constrain this effect by simultaneously fitting it and a to our angular distribution reconstruction of Ar^{+1} (Fig. 3) [12]. The projected statistics would allow us to fit other charge states +2 and +3 as well, achieving powerful redundancy of the model and making the systematic error smaller. Several other errors can be projected to improve with statistics.

An upgraded experiment would also include:

1) A larger MCP to reduce an error from the apparatus acceptance of 65% of the Ar^{+1} recoils (errors for this version shown in table). This error folds indirectly into the electric field and trap position errors.

2) A permanent mask installed on the MCP to monitor any position distortions from resistive anode nonlinearities. This is unimportant for analysis method I but very important for analysis method II, which we expect to be critical at lower E_β.

3) Better low-energy β singles calibration using interwoven ^{37}K trap measurements. At present our ability to determine the Fierz term is compromised by a relatively poor understanding of our singles E_β spectrum (from which we get our energy calibration) below 2 MeV. There is a 2.17 MeV γ-ray from the ground state of ^{38}K, and it appears there is a very small contribution of 2.7 MeV endpoint β's from ^{38}K g.s. that diffuses into the detection chamber. These together produce a 10% distortion of the singles E_β spectrum. We have shown in the past that ^{37}K does not suffer from this effect.

4) Simultaneous measurements of position on the MCP with respect to β's detected in the existing side CaF_2(Eu) detectors (see Fig. 1).

5) Measurement of the recoil momentum spectrum free of the β energy detection problems via a coincidence between atomic shakeoff e^-s and recoils to determine their TOF. We are in the process of experimentally testing this technique and expect it to have substantially reduced systematic errors, but stronger correlations between a and b. More details below.

^{38m}K β^+-ν Error Budget a=0.9981±0.0030(stat)

Error	**PRL**	**Proposed**
$\vec{E}$ field/trap width :	**0.17%**	**0.04%**
E field nonuniformity	**0.14%**	**0.03%**
β^+ backscattering bkgd	None	None
$E_{\beta+}$ Detector Response:		
Lineshape tail/total	**0.06%**	**0.03%**
511 keV Compton sum	**0.09%**	**0.04%**
Calibration, nonlinearity	**0.17%**	**0.08%**
MCP Eff[E_{Ar+}]	**0.07%**	**0.03%**
MCP Eff[θ]/XY position	**0.08%**	**0.04%**
e^- shakeoff [E_{recoil}]	**0.18%**	**0.08%**
Sum systematics	**0.37%**	**0.14%**
Total error	**0.48%**	**0.19%**

Table 1. Present ^{38m}K β-ν correlation errors, using our published technique of TOF and E_β information [4], and projected errors using the same TOF and E_β technique, based on larger MCP, use of background-free ^{37}K decay for energy calibration, and conservative improvement of $\sqrt{5}$ statistical error. Most systematic errors are determined by statistics-limited data evaluation. Further improvements are possible using all kinematic information.

e^--recoil coincidence method We show the sensitivity of the recoil momentum spectrum to these effects in Fig. 7. We also show the sensitivity to recoil shakeoff electrons and the ability to fit those simultaneously.

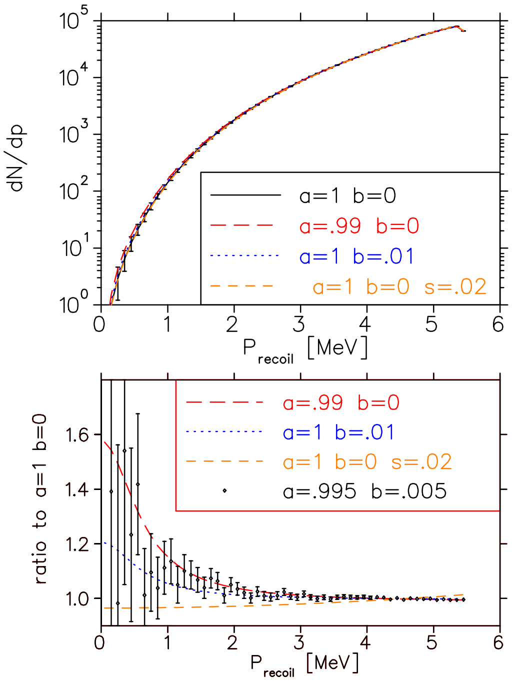

Fig. 7. Analytical simulation of the recoil momentum spectrum, which we would measure with atomic e^--recoil coincidences. The bottom figure shows the dependence on a and b. Although a and b are well-correlated, either one can be separated from the data simultaneously while allowing the shakeoff e^- dependence on recoil momentum to float. From 10^6 events (3 hours at 100Hz coincidence rate), the error on a is 0.001, and the error on b is 0.005. To reach superallowed Q-dependence error on b of 0.0028 would require 1 shift. To reach 0.001, with sensitivity to a window left open by $\pi \rightarrow e\nu$ decay, would require 10 shifts. (Here an accidental coincidence background is a substantial correction which must be known to <20% of its value, so we must achieve low background in the e^- detector.)

We also intend to pursue the Fierz term with the e^- detector. This technique has been demonstrated by our competitors in Berkeley [15]. The resulting recoil TOF spectra will not be systematically dependent on the β energy. Depending on the efficiency we achieve in e^- detection, our coincidence rate will be 10 to 50 times greater. We will investigate systematic errors in a ^{80}Rb experiment this fall, using the apparatus shown in Fig. 8. We expect considerable discrimination of e^- signal from a small β^+ background by MCP pulse-height. If this method becomes viable for use in ^{38m}K decay, we could achieve statistical errors of ≈0.001 on the Fierz term in 10 shifts, halving the world error and making us sensitive to a window in parameter space left open for slepton exchange [16].

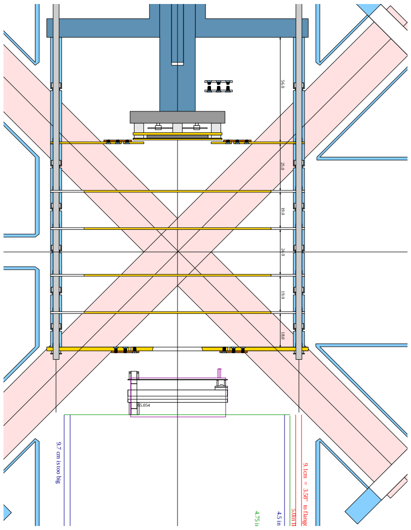

Fig. 8. The recently installed e^- detector is at the bottom, as mounted in place of the β telescope. A grid in front fixes the field in the ion travel region, and allows the MCP to be floated to different potentials to investigate dependence of efficiency on e^- impact energy. The present electric field is very uniform near the trap and where the ions travel, while POISSON calculations show that elevating the grid to close to the final electrode potential improves the uniformity closer to the e^- detector.

4 Experimental Equipment

We have described above the microchannel plate apparatus, and describe below its readiness.

5 Readiness

We will begin upgrading our MCP for positive ions with the arrival of a new postdoc in Feb. 2006. This is an elaborate job that requires careful integration with the existing electrostatic field assembly. We would expect to be ready for beam in late fall 2006.

The first version of the electron detector is installed and being tested now. If these tests go well this detector will be ready first. This detector makes very small perturbations of the electric field, restricted mainly to making the field more uniform in the region that ions do not traverse, and is mounted separately on a flange that replaces the β DSSSD/plastic telescope flange. So modifying and upgrading it is relatively very simple compared to modifying the main electric field apparatus.

We show a rough timetable to see how this fits in with the rest of the TRINAT program.

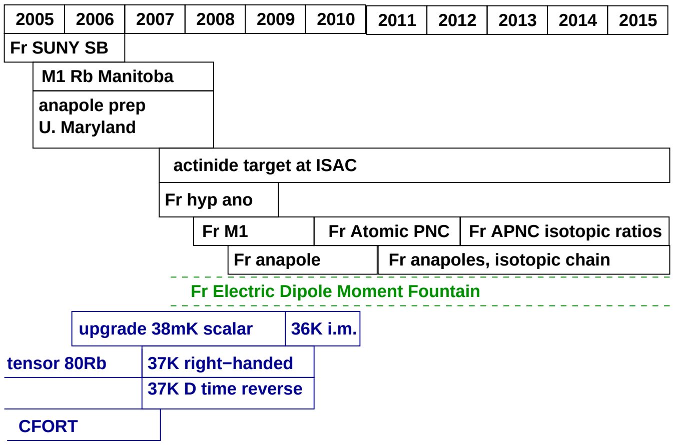

Fig. 8. Rough TRINAT timetable.

6 Beam Time required

We used about 30 shifts for E715 final data-taking. We expect to need 30 shifts for this upgraded experiment using the enhancements of the previous method, in order to achieve the errors in the table.

We would then expect 20 more shifts for the high-statistics atomic e$^-$-recoil coincidence, many of which would be to test systematic errors (e.g., running at different electric fields to determine efficiency dependence.) The goal here is to reduce errors to less than 0.001 in a and b.

7 Data Analysis

We use WestGrid for large Monte Carlo's. At some point we will have to retire our NOVA histogramming and will require DAQ help for ROOT-based system. Otherwise the present experiment will work with TRINAT's present DAQ.

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