Summary Sakharov's criteria to produce the baryon asymmetry would require new sources of CP or CPT violation. Sensitive null results in time-reversal violating experiments in many sectors provide a motivation for experiments in systems with fewer preexisting constraints. Time reversal-violating (TRV) correlations of 3 independent momenta from decays with 4-body final states have been searched for in a dedicated radiative K meson decay experiment, and in LHCb and BABAR B meson decays, but never in the first generation of particles.

We propose to measure a time-reversal violating asymmetry correlation of β^+, ν, and γ in the radiative β^+ decay of ^{38m}K. We have developed a GEANT 4 simulation with proof of principle that the background from positron decay can be handled, and a statistics-limited asymmetry of 0.01 can be reached per week of counting. A theoretical evaluation of this observable by Gardner and He has found: as much as 100% asymmetry is still allowed in our case by other experiments; final state contributions mimicking TRV are known and about 0.001; the more familiar Lee-Yang 4-fermion Lagrangian terms do not contribute; low-energy (MeV scale) phenomenology can produce TRV in such decays but still be hidden from previous experiments.

The TRIUMF EEC approved this experiment at high priority in June 2015. We report a refinement in the phenomenology that emphasizes measurement of higher-energy γ's, improved Monte Carlo simulations reflecting that change, and our plans in progress for adding γ-ray detection to TRINAT. Main additions are in blue.

1 Scientific value of the experiment: Time Reversal Violation in radiative β decay

1.1 Short overview of time-reversal violation

Additional sources of either time-reversal violation (TRV) or CPT violation are needed for Sakharov's mechanisms to explain the baryon asymmetry, the excess of matter over antimatter seen in the universe [1]. K and B meson decays thus far are consistent with one complex phase in the CKM matrix, the known source of CP violation, which falls many orders of magnitude short of what is needed. The equivalent phase in the neutrino mass matrix may be measureable in ambitious neutrino oscillation experiments. Continuing null results for the neutron EDM are close to ruling out certain explicit SUSY models as sources of the baryon asymmetry [2], and other EDM experiments have increased their sensitivity while still consistent with zero.

1.2 Previous TRV experiments in nuclear β decay

Immediately after the discovery of nearly maximal parity violation in the weak interaction, papers appeared suggesting T-odd nuclear beta decay correlations to search for TRV, most involving the spin of one particle and the two independent lepton momenta [3]. (Since the recoil momentum is given by the other two, correlations between the three momenta are trivial and do not constrain TRV.) It is clear from these papers that the original hope was that the amount of TRV could be as large as parity violation, as there were few experimental constraints. Two of these distributions have been pursued in earnest, and experimental sensitivity to D and R have become better than 10^{-3} and consistent with zero. These experiments establish direct limits on imaginary parts of the 4-fermion

Lagrangian scalar, tensor, and axial vector-vector interference terms, which describe a broad classes of physics, but not all possibilities. Most sources of TRV physics are indirectly constrained by null EDM experiments to produce $D < 10^{-5}$, if the possibility of cancellation between different physics sources making the EDMs is ignored. Leptoquark exchange has been constrained to contribute less than 10^{-4} to D [4], not by EDMs, but by experiments with no time-reversal violation such as atomic parity violation.

These sensitive null results in experiments directly involving spin provides motivation to look at other possibilities.

1.3 TRV in correlations of 3 independent decay momenta: examples from particle physics

We propose in the next section one of a different class of experiments involving correlations of 3 momenta in 4-body final states, not involving any spin. We first mention examples from particle physics.

TRV correlations have been pursued in radiative K decay in a dedicated experiment at INR in Moscow, where a TRV asymmetry consistent with zero of -0.015 $\pm$ 0.021 was observed [5], and several rounds of theoretical calculations of final state corrections were done [6].

Recent analyses of 4-body D meson decays at LHCb are reaching statistics-limited TRV asymmetry uncertainties as small as 0.003 [7], with similar sensitivity achieved from reanalysis of BABAR data [7], though none of these involve the photon. A general formalism and consideration of such experiments is in Ref. [8].

2 TRV in radiative β decay

A new source of time-reversal symmetry violation (TRV) has been proposed [9]. It could produce TRV asymmetries in radiative beta decay that are still allowed to be as large at 100% in some cases. We try to highlight the detailed results of Ref. [9] here.

2.1 A new physics term that generates photons with the weak decay

The standard model of particle physics contains a higher-order term, generated by QCD, that directly couples photons and the weak interaction together within nucleons— the original theorists who pointed this out had in mind additional ν interactions producing γ's in accelerator-based ν detectors [10]. It was further pointed out by Gardner and He that this mechanism produces a contribution to the Lagrangian for neutron β decay that looks like the usual semileptonic vector current with an electromagnetism tensor $F_{\nu\rho}$ tacked on, made antisymmetric by the QCD part [9]:

$$L = -\frac{4c_5}{M^2}\frac{eG_F V_{ud}}{\sqrt{2}}\epsilon^{\sigma\mu\nu\rho}\bar{p}\gamma_\sigma n\bar{\psi}_{eL}\gamma_\mu\psi_{\nu,L}F_{\nu\rho} \quad (1)$$

If the coefficient c_5 is allowed to be complex, which would of course need physics beyond the standard model, then interference between such a term and the standard model's vector current term for nuclear β decay produces a contribution to the decay rate [9]:

$$|\mathcal{M}_{c5}|^2 \propto \frac{Im(c_5 g_V)}{M^2}\frac{E_\beta}{p_\beta k_\gamma}(\vec{p_\beta} \times \vec{k_\gamma}) \cdot \vec{p_\nu} = -\frac{Im(c_5 g_V)}{M^2}\frac{E_\beta}{p_\beta k_\gamma}(\vec{p_\beta} \times \vec{k_\gamma}) \cdot \vec{p_{\mathrm{recoil}}} \quad (2)$$

where we substitute neutrino momentum for sum of β and recoil momenta $\vec{p_\nu}$ = -$\vec{p_\beta} - \vec{p_{\mathrm{recoil}}}$, and note that the triple scalar product of like vectors vanishes.

By classically reversing either time or $\vec{r}$, this product of three momenta can be seen to be time-reversal as well as parity violating.

This term directly produces the γ, and, remarkably, it is not suppressed by the fine structure constant α. A TRV experiment looking for this physics must measure the relatively rare radiative decay branch, but gains direct sensitivity to this class of new physics.

This term is proportional to g_V, so involves the vector current, not the axial vector current driving Gamow-Teller decay. Of the isotopes trapped in TRINAT, the pure Fermi decay of $^{38\mathrm{m}}$K and the mixed Fermi/Gamow-Teller decay of ^{37}K are suitable. Ref. [9] calculated ^{35}Ar, which has almost the same β decay Q-value (energy release), so we adopt those results for planning purposes. A figure of merit is the experimental uncertainty, which for small theoretical asymmetry $\mathcal{A}$ is given by $\mathcal{A}\sqrt{\mathcal{BR}}$, where BR is the branching ratio governing the counting statistics. The theoretical asymmetry is roughly scaling with the square of the lepton momentum, which has maximum value 5 MeV instead of 1 MeV, and in Table I of Ref. [9] is 20-50 times greater for ^{35}Ar compared to the neutron. There is a similar scaling of the BR with atomic number Z. The result is an uncertainty achievable for a similar number of beta decays about 200 times better for ^{35}Ar compared to the neutron, with similar answer for ^{37}K or $^{38\mathrm{m}}$K.

2.2 Standard Model contributions mimicking TRV

Reversing momenta of decay particles is not exactly equivalent to time reversal. The outgoing particles interact electromagnetically, and that part is not reversed.

False asymmetries from these 'final state' interactions have been calculated, and vary from 0.8 to 1.6x10^{-3} from 10 to 100 keV for ^{35}Ar [9]. The result scales by $(1-(\frac{M_{GT}}{M_F})^2/3)/(1+(\frac{M_{GT}}{M_F})^2)$, so is 1.1 times larger in $^{38\mathrm{m}}$K and 0.7 times the size in ^{37}K.

Gardner notes that that scaling suppresses the ^{19}Ne final state interactions by a factor of 20 [9], making it an interesting future candidate for an atom or ion trap experiment.

2.3 Constraints on TRV in radiative β decay from other sources

2.3.1 Constraints from 4-fermion Interactions

Gardner and He calculated the contributions to radiative beta decay to physics from 4-fermion interactions. Characterized by their Lorentz transformation properties, these tensor, scalar, and axial-vector/vector interference [3] have all been shown to be small enough in D and R experiments that they would make less than 10^{-6} contributions to the radiative β decay experiment considered here [9].

2.3.2 Constraints from EDM null results

We overstated the situation concerning EDM constraints in our LOI, going beyond careful statements in Ref. [9]. The situation is now clearer in the literature. The result remains that EDM constraints are not important to the source of new physics proposed, but we owe the committee some details here.

We were logically incorrect to say that null EDM experiments can't constrain a spinless observable. It is partly a question of the order to which one must calculate. E.g., even the TRV in the standard model, which does produce TRV in spinless observables, generates EDMs at high enough order (three loops for electron EDM). In contrast, there is a well-known TRV term in the fundamental QCD Lagrangian that depends on spin and directly produces EDMs, and therefore is known to have a coefficient Θ_{QCD} less than 10^{-9} or 10^{-10}. Another example is CP odd correlations in the 3-photon decay of orthopositronium: EDM null results constrain some general sources of new physics so their contributions are small, but explicit models, such as exact cancellations from scalar and pseudoscalar exchange particles, can evade such constraints [13].

A paper by Dekens and Vos [14] has clarified our situation. They consider three effective field theory operators at TeV scale that generate both a TRV radiative nuclear beta decay asymmetry and, with higher-order corrections, EDMs. One of these EFT operators is even of similar form to Eq. 1, though it does couple to quarks directly and is not emergent from QCD. That is not a trivial concern, because they can apply perturbation theory to quarks that can't be done with nucleons at low energy [John Ng, private communication]. They quantify the resulting constraints on the coefficients of their EFT operators that result from EDM null searches, and state that this constitutes a demonstrative example that EDM null results can provide constraints on new physics that could contribute to radiative beta decay.

However, even if the coefficients were of order unity, these EFT operators produce radiative beta decay TRV asymmetries of 10^{-10}, which is clearly unmeasurable. Dekens and Vos use EDM null results to reduce the possible TRV asymmetry to 10^{-12}, which is impressive overkill. The structure of their EFT term scales explictly by (lepton momentum)^2/(mass scale)^2, which naturally kills TeV-scale contributions to few MeV-scale β decay by 10^{-10}.

Thus Dekens and Vos have clarified for experimentalists that any measureable new physics contributing to radiative nuclear β decay through such terms is not going to have TeV scale. The experiments we plan are not complementary to high energy experiments.

Gardner and He implicitly assumed these scales when in Ref [9] they considered much lower-energy scales:

2.4 Physics and explicit model considered by Gardner and He

The physics example given by Gardner and He represents a class of physics that can generate large TRV asymmetries in radiative β decay while still evading other experimental constraints. The explicit physics model they consider has low energy scale $M \sim$ MeV. It involves a new sector of particles that strongly interact among themselves, but the c_5 coupling to our standard model can be small. The key component is ρ-like mesons with masses $\sim$ MeV so that they have maximal contributions at the energy scale probed by β decay. Such models may sound a little contrived, but they have remarkably few constraints, and could produce dark matter candidates as well [9]. (Note that dark matter sectors that interact strongly with themselves but weakly with standard model particles have strong motivations [15].) In this way, charged current experiments through radiative decay can be used to explore some aspects of neutral current physics that are otherwise difficult to measure.

Consequences of the direct contributions of such physics can be considered, but since they involve QCD-like interactions, calculations involving them are not perturbative. So there is no clear path to calculating higher-order constraints from other physics. Both high-energy colliders and rare decay efforts can look for such particles in missing momentum experiments, but will likely lose them in backgrounds– the broad resonances produced may not be recognizable as particles.

2.4.1 The main constraint is from radiative neutron decay

The radiative β decay of the neutron has been measured [16], an experimental tour de force in a clean theoretical system. The NIST collaboration's final result achieved $\sim$ 5% accuracy on the branching ratio $3.35{\pm}0.16{\times}10^{-3}$, 1.7 σ higher than the calculation of $3.08{\times}10^{-3}$ [17]. The branching ratio has contributions proportional to $|c_5|^2$, less sensitive than the TRV asymmetry, which is linear in c_5 because it is from an interference term. Treated as a constraint on this interaction (rather than a 1.7 σ discovery...) the result is $Im(c_5)/M^2 \leq 8\text{MeV}^{-2}$, which allows the TRV asymmetry to be as large as 10% in neutron β decay [9]. At the higher lepton momentum of the cases we have in mind, the constraint grows weaker, and the asymmetries in Table I of Ref. [9] can still be as large as unity in principle.

2.5 Correction to phase space

Gardner has clarified a key point for us: the phase space for any interaction that emits the photon with the other 3 products together produces a much harder gamma-ray spectrum than classical bremsstrahlung. Bremsstrahlung comes from the acceleration of the β's charge alone, and makes the well-known $1/E_\gamma$ dependence. In contrast, the 4-body phase space [11] produces an E_γ dependence that looks more like the other leptons, peaking at roughly 1/3 of the maximum energy (5.1 MeV for ^{37}K or $^{38\text{m}}$K) and extending out to the endpoint. The predicted spectrum is shown in Fig. 2.

This fact has simplified our experimental strategy. We originally presented a plan to measure the standard model bremsstrahlung dependence down to low E_γ and look for its asymmetry. To optimize low-energy detection, an elaborate system to eliminate the 511 keV annihilation radiation from the γ detectors was needed, requiring both 511 full-energy peaks in a segmented detector surrounding the β detector. Appropriate few-mm thick high-Z scintillators can even have good efficiency below 200 keV while suppressing 511 keV detection.

Concentrating on $E_\gamma \geq 511$ keV simplifies the β^+ detector, and also allows for the use of normal-sized γ-ray detectors. We will still attempt to look below 511 keV: see the next section.

3 Description of the experiment and equipment:

Using the TRIUMF neutral atom trap (TRINAT), we can detect the recoiling nuclei with only a few 100 eV of kinetic energy from the beta decay of laser-cooled and trapped radioactive atoms. Measuring coincidences with βs then lets us measure the ν momentum event-by-event.

Places for γ-ray detectors in the present TRINAT detection vacuum chamber are shown in two places in Fig. 1, which we will refer to as Geometries A and B. We would use present TRINAT features including: β^+ telescopes; the electric field to gather ions produced by the decay; the ion MCP to detect the ions; the electron MCP to detect shakeoff electrons, adding extra rejection of backgrounds. The flanges for the β^+ telescope would be kept this size.

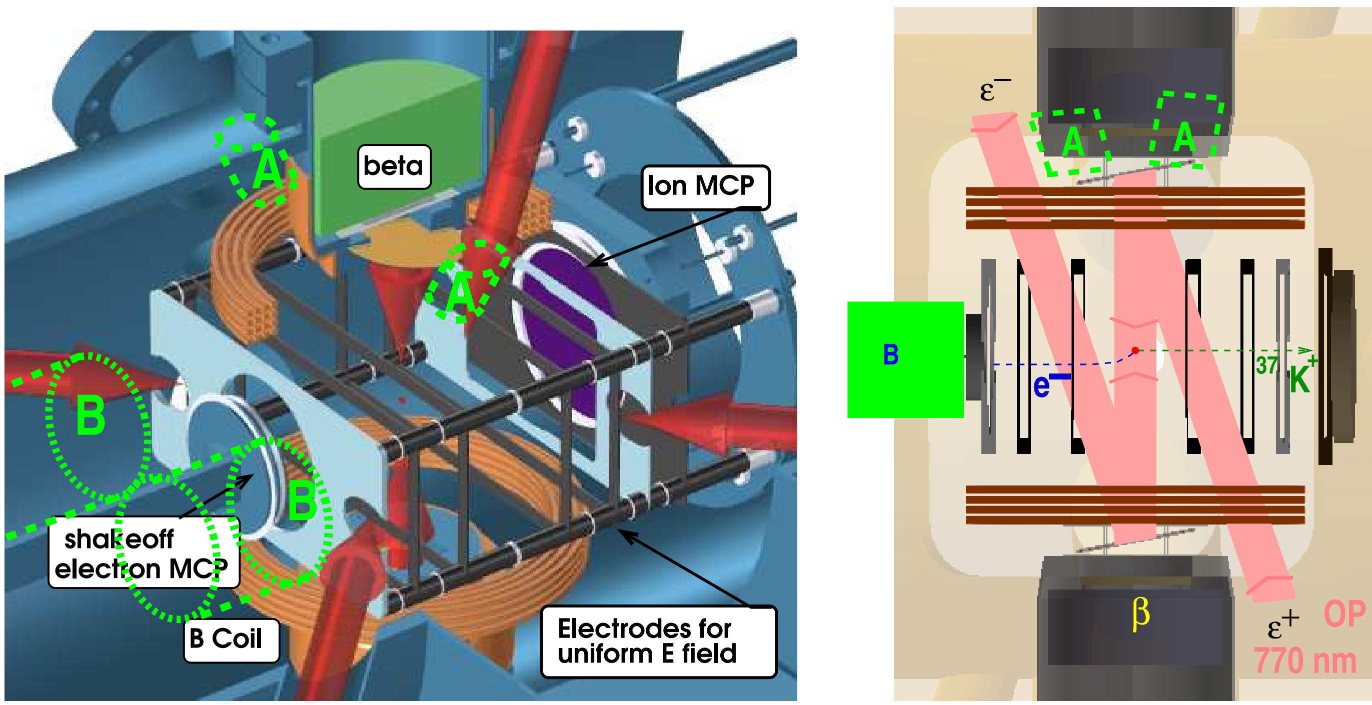

Figure 1: Two views of the present TRINAT detection magneto-optical trap (MOT), optimized for polarized experiments by optical pumping, showing places to add γ-ray detectors in Geometries A and B. Geometry A's γ detectors are at ± 35 degrees with respect to the vertical β detector. The optical pumping and MOT vertical beams share a path, reflecting off a thin mirror in front of the β detector to provide better dΩ for βs. The β detector has a twin opposite it for asymmetry experiments. The near-uniform electric field of $\sim$ 1 kV/cm collects ion and shakeoff e^- to MCPs. The in-vacuum B field coils produce gradients of $\sim$ 10 g/cm. Scale is set by the ion detector 80 mm diameter.

γ **detectors** Detectors must be added to see the radiative γ-rays. Ports at $\pm$ 35 degrees to either side of the β^+ telescopes can be used for the γ-ray detectors by using re-entrant flanges with beryllium windows (Geometry A in Fig. 1). So we explore below such a geometry with a GEANT4 simulation. The present GEANT4 simulation suggest the MOT B field coils are not producing significant backgrounds from scattered β^+'s, but they could be placed outside the vacuum in non-polarized experiments if necessary.

3.1 Simulation of time reversal by momentum flips

Time reversal in the correlation of Eq. 2 can be simulated by flipping all 3 momenta (γ, β, and recoil), then adding smooth rotations to choose various combinations of detectors.

One such asymmetry would keep γ and β in the same detectors, but take the difference in number of recoils moving initially away from and towards the TRINAT ion MCP. We detect such ions and compare them in our β-ν correlation experiments [23], so are confident we could detect these with systematic error less than 0.002.

Another asymmetry would keep β and recoil momenta the same, but take the difference between count rates of two γ detectors as in Geometry A. To test the symmetry of the γ-ray detectors, we would study coincidences between pairs of β-γ, nuclear recoil-γ, or shakeoff e^--γ, which are not TRV. For concreteness, we consider primarily this γ asymmetry in the simulation below.

3.2 γ-ray detection

A key concept is that we will require the β^+ to reach the β^+ ΔE-E telescope. Clearly, one cannot completely avoid a β^+ scattering on material before reaching the β^+ telescope, so the challenge is to prevent bremsstrahlung from such scattering from reaching the γ detector. Our atom trap is a natural geometry for this, because there is not much material near the trapped atoms.

3.2.1 Need for β^+ emitters

The vector current in Eq. 2 requires, considering isotopes trappable by TRINAT, β^+ emitters. Since the coincidence γ-β backgrounds from 511 keV annihilation present difficulties, we detail our reasoning here.

^{38m}K is a pure Fermi decay, so it is sensitive to the physics of Ref. [9], and it has about 4 times greater yields from TiC targets than ^{37}K. This is our best choice from trappable isotopes.

The mixed Fermi/Gamow-Teller decay of ^{37}K would also work well: Compton scattering of the 2.7 MeV γ's from the non-g.s. 2% branch will produce some contamination.

We can find no suitable trappable cases for β^- decay. In allowed decay, to have a significant vector current, the decay must proceed to the isobaric analog state, but such decays are energetically forbidden in self-conjugate decays with higher Z than the neutron and tritium. There are isospin-forbidden Fermi decays caused by isospin mixing of low-lying states with the high-lying analog state, but all cases we find have both significant discrete γ-ray production and rather small Fermi matrix elements.

The vector current can contribute to first forbidden decay. The selection rule [18, 12] is that the vector current does not contribute to $0^- \to 0^+$ (e.g. ^{92}Rb), nor to first forbidden unique decays with angular momentum change of 2 units (e.g. ^{42}K $2^- \to 0^+$), so these can be used only as tests or to search for other TRV physics than Eq. 2. Other first forbidden transitions do have vector current contributions [12], but all such β^- decay in trappable K or Rb isotopes (such as ^{93}Rb) have a large γ-ray multiplicity at higher energies than 511 keV or prohibitively long half-lives.

The short-lived potassium isotopes are only available from TiC targets. We will use for tests ^{92}Rb, from more commonly available UCx targets, running parasitically to our approved ν spectrum experiment.

3.2.2 GEANT4 simulation results

We show in Fig. 2 the results of a GEANT4 simulation for background in the γ detectors, compared to the predicted γ spectrum from the correct phase space (arbitrary normalization for clarity). The β^+ decay Q-value is 5.021 MeV.

A large background in the γ detector is reduced by requiring the β^+ energy in the plastic to be greater than 600 keV, leaving the green curve. Note that the standard model bremsstrahlung (dark blue curve) is still overcome by background, and to see this in the geometry shown would require a pair of 511 annihilation γ's in the BGO detector (black curve). It is helpful that γ's from the $\beta^+\nu\gamma$ interaction extend to higher energies (red curve), so without the 511 coincidences the experiment is viable for those.

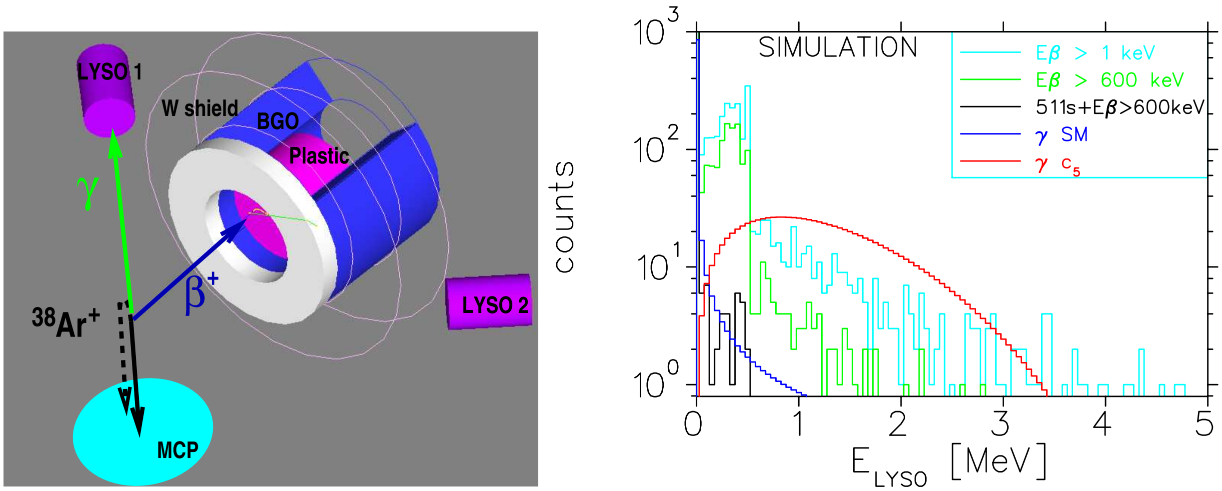

Figure 2: GEANT4 simulation of the geometry shown, similar to Geometry A of Fig. 1. The red curve includes the correct phase space for the γ emission for the 4-body phase space of the new interaction of Eqs. 1 and 2.

To avoid cumbersome geometries with long light guides to keep PMT μ-metal shielding away from the atom trap region, we are developing SiPM readout. We will soon test 25x25 mm NaI(Tl), BGO, and LYSO with 12x12 mm SiPM readout– the literature has good examples of using SensL off-the shelf SiPM without major development, particularly with the faster LYSO. In such compact geometries, high Z and density are critical for good efficiency and photopeak fraction (which is 22% for NaI(Tl), 52% for LYSO, and 58% for BGO at 25x25 mm for 1 MeV γ's), We also prefer non-hygroscopic materials for more flexible geometries, avoiding aluminum cans that produce eddy currents near the atom trap. An LYSO crystal of this size has several kHz of natural background– in double or triple coincidence this looks manageable, though not ideal. Our study might motivate a grant request this fall for one of the more modern scintillator alternatives with high density, high Z, good timing and energy resolution, and minimal natural background (cerium bromide or, since it is denser, GAGG(Ce)). The timing is to minimize accidental coincidences, while the energy resolution helps to understand and reject backgrounds.

Geometry A (Fig. 1) occupies two viewports not needed for our ^{92}Rb ν spectrum experiment (which among other things has no need for nuclear polarization and probing) and we intend to test this in September, following work starting work in June with a summer undergrad characterizing this setup.

Geometry B of Fig. 1 involves a redesign of the electron MCP mount for shakeoff electrons on an 8" diameter re-entrant flange, leaving good spacing for two or four γ detectors. Two are at 90 degrees with respect to the β^+ direction, so have more sensitivity to the triple scalar product, and also have roughly 3x the solid angle of Geometry A. TRINAT used a similar geometry for ^{80}Rb recoil spin asymmetry experiments [19]. This could be compatible with the spin-polarized ^{37}K experiments, but issues like small eddy currents making polarization more difficult, along with an increased surface from which β's can scatter, likely conflict with the high degree of accuracy now needed in the ^{37}K program. There is also a small perturbation of the ion collection electric field from the larger ground area extending beyond the physical extent of the electrodes. These are among the reasons why we are still asking for dedicated shifts for this TRV experiment.

3.2.3 Further considerations and improvements

This is an interesting γ-ray spectroscopy experiment, and further optimization of the simulations is ongoing.

Accidental coincidences are not shown, but become a significant correction at the 400 Hz decay rates planned per detector, because of the large background suppression needed. This is one reason we prefer LYSO's speed over BGO.

Much of that raw rate in the γ detectors is from direct β^+s. We plan to use the old-school technique of adding 2.5 cm of Be in front of the γ detector to stop the β^+s while minimizing 'outer' bremsstrahlung γ production, though anticoincidence with a thin plastic might be more effective.

Given the concentration on higher-energy γ's, we now plan to use passive shielding between the γ detector and the β^+ detector. This avoids the complex and efficiency-limiting geometry requiring a 511 photopeak pair in a detector surrounding the β^+ detector. More passive shielding may be necessary, in which case the BGO detector shown could be changed to tungsten alloy shielding.

3.2.4 Real term: previous measurements of radiative β^- decay of nuclei

The radiative γ branch in ^{38m}K produces an 0.002 correction in our β-ν correlation measurement [23], and it would be helpful for our next generation experiment S1070 to test the calculation directly. There have been many efforts to measure "inner bremsstrahlung," dating from at least 1945, and we do not review the entire field here. Bienlein and Pleasonton in the well-understood Gamow-Teller decay of ^{6}He [21] saw substantial deviations from theory below 0.3 MeV γ energy, blamed on not understanding the detector lineshape; the radiative branch is much smaller in ^{6}He than the 5-7% branch in ^{37}K and makes for a much more difficult measurement. Boehm and Wu have γ-ray spectra in agreement with theory from 25 to 100 keV photon energy using NaI for ^{147}Pm and ^{35}S [20]. We do not underestimate the difficulties here, but we believe accurate measurements can be done in optimized geometries.

4 Readiness

The trap is working for this purpose. We require development of γ-ray detection with SiPM, which we are pursuing now with a summer undergrad.

Yields: ISAC delivered in June 2014 more ^{37}K than before by factors of three, reaching reliable yields of 1x10^8/s which allowed us to trap 10,000 atoms and count 5/sec beta-recoil coincidences continuously for 10 days spread over 3 weeks. Yields of ^{38m}K are a factor of four higher than ^{37}K from this material. The yields were due to improvements in TiC particle size and are expected to be reproducible by the target chemists. It is these higher yields that have encouraged us to make proposals such as these requiring coincidences and smaller branches.

5 Estimated Uncertainties and Beamtime required:

Our efficiency for collected recoil ions in our electric field is about 7%– roughly 15% of the recoils are ions in positron decay, and our MCP efficiency is 55%. For 40,000 atoms of trapped ^{38m}K and 1.5% solid angle for the shown β^+ detectors, we need half a day to collect 3% statistics and 5 days for 1% on a TRV asymmetry between γ-ray detector pairs.

We will do tests parasitically with existing ^{92}Rb shifts for its ν spectrum, so we do **not** ask for the 2 1/2 days of shifts for 'testing' that were in the original proposal.

Request: We ask for 15 eight-hour shifts of dedicated ^{38m}K time. All the schemes we have compromise something from the approved ^{37}K and ^{38m}K correlation experiments (E field uniformity and/or diagnostic ports), so we require dedicated beamtime.

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